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ABSTRACT

The course outlines presented in this report are intended to be used to teach astrophysics to nonscience majors at the junior and senior college level. An extensive set of notes are included which can be useful to an instructor as guidelines for presentation. Additional equipment and references for use in teaching astrophysics are suggested. (SA)

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University of Illinois at Chicago
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INTRODUCTION TO ASTROPHYSICS

CURRICULUM DEVELOPED
BY
FACULTY WORKSHOP AT
UNIVERSITY OF ILLINOIS AT CHICAGO
SUMMER 1974

U.S. DEPARTMENT OF HEALTH.
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TABLE OF CONTENTS

Page

FOREWORD..1

PART I: INTRODUCTION TO MODERN ASTROPHYSICS "TRADITIONAL" COURSE OUTLINE....................................16

Time Schedules for "Traditional" Course.............30

PART II: INTRODUCTION TO MODERN ASTROPHYSICS "CONCEPTUAL" COURSE OUTLINE....................................31

Time Schedules for "Conceptual" Course.............41

NOTES AND COMMENTS ON COURSE OUTLINES.........................42

APPENDIX A: RECOMMENDED SLIDES.............................152

APPENDIX B: SOURCES FOR FILMS, PHOTOGRAPHS AND SLIDES......159

APPENDIX C: RECENT POPULAR ARTICLES FOR REFERENCE..........163

APPENDIX D: PARTICIPANTS OF FACULTY WORKSHOP...............164

FOREWORD

The past decade and a half has witnessed an unprecedented surge of interest in the astronomical sciences on the part of the general public. Young people especially have been drawn by recent dramatic discoveries in the field, made possible in large part by equally dramatic technological advances. Speculations about the nature of such imagination-stimulating subjects as quasars, pulsars, gravitational collapse, black holes and a whole panoply of new-found objects have focused the layman's attention upon astronomy and astrophysics as a very contemporary and exciting discipline.

College enrollment in undergraduate courses in both astronomy and astrophysics has mushroomed at such a rate that many physicists without prior experience in the field, have been called upon to develop and teach curricula in the field. They have risen to the occasion, for the most part, with energy and ability but with the slightly uncertain trepidation of adventurers in a foreign land. The landscape has an air of slight familiarity from the travel folders, but the confident, easy, getting about of the native is missing, and the traveller hardly feels capable of serving as a tour-guide.

In the summer of 1973 we conducted an NSF sponsored, four-week summer session for 24 college and university physics faculty members who were in the position of teaching astronomy/astrophysics without formal backgrounds in the subject themselves. This experience furnished us with valuable insight into the problems and needs of schools that are seeking to develop an undergraduate curriculum in the field without the base of an established professional astronomy faculty. Among the many things we learned about such curriculum developments, three are especially worth mentioning here.

First, the need for guidance from the professional astronomy community is keenly felt by physicists new to the field. This was repeatedly emphasized by participants in the 1973 summer program. These were all competent physicists, all Ph.D.'s, many from top graduate schools, and they reported few difficulties in mastering the physics of astrophysics. However, they did experience difficulty in knowing how the curriculum should best be designed for students at various levels: what to present, where the emphasis should be placed, how to provide the background for students to understand the new developments. In short, there does indeed appear to be a need for assistance in curriculum design for physics faculties in colleges and universities attempting to meet the demand for courses in astronomy and astrophysics at the undergraduate level. No doubt the best solution to fulfilling the demand would be to add professional astronomers and astrophysicists to physics faculties, but few schools appear willing to do this at present, feeling that until the astronomical curriculum offerings become more extensive such a step is not economically justified. Thus it seems a foregone conclusion that in most cases extension of science offerings into the astronomical realm will of necessity have to rely largely upon physicists who are presently attached to physics departments to design and teach the astronomy and astrophysics courses.

The second major finding from the 1973 summer session was that interest among colleges and universities in instituting courses in astronomical science is indeed widespread both numerically and geographically. Despite the fact that the 1973 summer session was not widely publicized and was being given for the first time, there were more than ten qualified applicants for each opening. Nearly every state was represented among the applicants, and when allowance was made for the northeast and west coast concentrations of institutions, the geographical distribution of applications was fairly isotropic. Applications were received from schools of all sizes, from state universities down to small private colleges with some emphasis upon newer publicly supported institutions of medium size.

The chief appeal of the 1973 summer session seemed to lie in its attempt to provide a review of areas of modern astrophysics not familiar to the participants. As we had anticipated in designing the 1973 session, few of the participants had been able to take the time to develop an easy familiarity with the very wide range of subject matter currently encompassed by modern astrophysics. While well grounded in basic physics, and indeed expert in their own areas of specialization, they were not in touch with some recent developments in astrophysics except perhaps on a superficial level and welcomed more detailed reviews of the topics especially to the extent that the reviews were designed to present the subjects in ways in which they could be taught to students not majoring in astronomy or astrophysics. It was in anticipation of this need of the participants that the 1973 summer session concentrated upon reviews of selected areas and topics in astrophysics chosen with a view toward what students, especially undergraduate students, are likely to find most stimulating and also with a view toward demonstrating the wide range of physics that has to be brought to bear upon many of the problems in modern astrophysics. This kind of guided tour through modern astrophysics emphasizing what can be taught to undergraduates and the way in which the ideas can be conveyed without overly heavy demands upon math and physics backgrounds on the part of the student proved to be right on target in filling the needs of the participants. They needed some guidance toward source material inasmuch as the astrophysical literature has grown quite extensive in recent years. Much of it, even the review articles and papers, demand a fairly easy familiarity with a sizeable body of background material, in many cases at a rather high level of sophistication. It is not surprising, therefore, that the newcomer to the discipline would welcome some guidelines to the maze.

From what we learned in the 1973 summer session about the needs of physicists beginning to teach astrophysics at the undergraduate level, the idea for the 1974 Astrophysics Curriculum Summer Workshop developed. To respond in part to these needs, we invited a dozen prominent professional astronomers and astrophysicists from several large University Astronomy departments to meet for two weeks at UICC to design a series of course outlines in astrophysics for use at several levels (mainly undergraduate) by physicists newly entering into teaching in the field. The aim here was to suggest in detail what, in the experience of these astronomers, should profitably be included in courses of various lengths at several levels, how this material might best be organized and how it might be most effectively presented. The recommendations that came out of the deliberations of this group during the NSF sponsored 1974 Astrophysics Curriculum Workshop are contained in this document. They are the end products of an impressive number of total man-years of teaching and research experience in astrophysics and represent a collective, seasoned judgement as to appropriate course content and organization for several groups of students at different levels.

The course outlines given here do not follow either the organization or the emphasis of the majority of existing textbooks written for the undergraduate student. In many respects these departures from the traditional presentation are the most significant features of these new courses. Astronomy texts as a whole still tend, for the most part, to follow a long and venerable tradition, and the method of presentation continues generally to emphasize the astronomical side of the subject rather than the physics, especially the unifying influence supplied by modern physics. We felt, from the beginning, that the physicist teaching the subject would be strongly impelled by background and ingrained point of view toward a unified, conceptual, physical presentation rather than the traditional approach of most astronomical texts, and with this in mind, we attempted to construct courses that would appeal to the physicist as logical and orderly, hopefully achieving an arrangement and emphasis that he would feel at ease with to the benefit of his own teaching. This was not a simple goal to reach, as it turned out, and considerable thought and discussion by participants of the workshop went into deciding first whether this philosophy was sound and then how it could be implemented.

The Workshop participants included several who would classify themselves as astronomers, having received traditional professional training in astronomy departments and having received their degrees in astronomy. The rest considered themselves to be astrophysicists, having been trained as physicists with degrees in physics in most cases, even though they now regard themselves as working members of the astronomical community and are members of university astronomy faculties. It was not surprising in view of these differences in background that these two groups took somewhat different views about the philosophy of arranging courses to emphasize the unifying physical concepts: those with physics backgrounds tended to favor this approach, supporting our thesis that physicists generally would feel more at home teaching the subject along these lines. Most of the astronomers, however, were not so eager to scrap the traditional approach which felt so familiar to them and which has stood the test of time. This divergence of viewpoint led to the design of two separate sets of curricula for undergraduate non-science majors. One, developed by a group made up mainly of astronomers, will be referred to as the "traditional" curriculum; the other, developed by a group consisting mostly of astrophysicists will be termed the "conceptual" approach. Actually the former, despite its traditional name, differs considerably from the organization of most astronomy texts, and when the curricula are compared, it is interesting to note that the two independent approaches are not very dissimilar after all.

It may be of interest to future writers of introductory textbooks in astronomy to study the organization of both these courses. It is perhaps significant that the astronomers themselves, as a result of considerable thought and discussion, chose a format that represents a departure from that in common use in most texts. The break with the traditional form of presentation represented by the conceptual approach of the astrophysicists becomes most evident in the design of the various "mini-courses" intended as short introductions to special topics. In each of these the unifying theme is the physics involved, and here the leitmotif dictates the astrophysical considerations and examples to a large extent.

The course outlines presented in this report were developed with several different types of students in mind. The first pair of courses (a "conceptual" and a "traditional" course) was designed at the introductory level primarily for the non-science major student. In many schools such a course may be an option among several to satisfy the minimum science credit requirements and as such may be the only contact the student will ever have in college with a modern physical science. A majority of these students will have forgotten most of the little math they may have once known. In fact, a certain proportion of them, and not a negligible fraction either, will take a perverse pride in being non-mathematical. Thus, it is a real challenge to teach a science like astrophysics to the non-science major, and such a challenge deserves both the best teaching talent and the greatest care and conscientious course preparation. Experience has shown that a skillful teacher can get across a surprising amount of physics and astronomy and can convey qualitatively the essence of many quite complex and sophisticated phenomena in astronomy to these students. It is not surprising, therefore, that the Workshop participants spent much time and care in the design of these introductory courses. It is expected that these courses will prove the most demanding to teach effectively, but they offer what may be the only opportunity to show the non-science student the power of the scientific method and the beauty of intellectual achievement that it represents. It has been said that astronomy is the most accessible of the sciences for the layman. It is certain that he approaches it more willingly and with less antipathy than perhaps any other physical science and because of this and also because the field encompasses so much of both classical and modern physics it is the vehicle par excellence with which to convey science to the non-scientist or even that increasingly prevalent atavist, the anti-scientist.

With the special importance of these introductory courses in mind, considerable amounts of supplementary material, notes, and comments have been appended to the course outlines as an aid to the teacher. The courses have also been designed for two lengths; the school quarter of ten weeks having approximately 28 class periods and the semester of 15 weeks with about 40 class periods. It is generally much harder to give a good one quarter course of either kind than to do it in one semester, and the semester length is much to be preferred especially for the non-science major because the more relaxed pace possible with 40 class sessions makes development of the unfamiliar concepts much easier. Also, more material can be included in the semester length and more of the intriguing contemporary topics the student may have seen mentioned in newspapers and news magazines can be treated. Following each of these course outlines are suggested schedules for both quarter and semester length presentations. These schedules will give the teacher a fairly good idea of suitable emphases for the various topics.

One of the hardest things for an expert in a discipline to do in designing curricula in that field is to pare away all the things which may have been or appeared to be of importance when he learned the subject but whose importance has diminished with time or which are really not important for the particular student to be reached. Thus, it was hard for the astronomically trained group to dispense with many of the topics such as astronomical coordinate systems and time that occupy a sizeable part of the classical introduction to astronomy.

It is equally hard for the physics trained people to avoid being overly quantitative, overly mathematical. Few physicists can resist showing how Kepler's second law arises out of conservation of angular momentum, not realizing that even the concept of angular momentum itself is foreign to most students who would be taking this non-science major course. The idea that conservation of this quantity is a consequence of the isotropy of space is far beyond these students' ken, although a good argument can be made that this sophisticated connection between Kepler's law of areas and the large scale distribution of matter in the Universe is really the best way to introduce Mach's Principle and the related set of ideas upon which general gelativity rests. It is a curious quirk of human intellect that it is often easier to lead the student untutored in science to an appreciation of such a great, generalized principle than it is to lead him through the simple mathematical steps by which one can show that Kepler's second law follows from conservation of angular momentum.

An extensive set of notes is appended to the outlines. These are addressed primarily to the instructor and they attempt to point out a prudent path in the matter of level of presentation as well as content. These notes should not be thought of as an abbreviated text. It should be clear on casual inspection that they are intended only as guides for the instructor, and he should not attempt to teach from them. The notes are also not meant to suggest by their detail the relative emphasis recommended for various topics. For example, the detail included in such areas as stellar structure and evolution in the "traditional" outline is considerable and implies an emphasis on this area that is out of keeping with the balance most teachers would seek in an introductory course. For matters of balance and emphasis, the suggested course schedules are better guides than the notes. In any case, the individual instructor has considerable leeway in emphasis and should use his own judgement. The main caution that applies for a course given to non-science majors is to avoid too much mathematics and too heavy emphasis upon details that presuppose a physics background.

Originally, we had planned to provide another pair of course outlines paralleling those given but designed specifically for science majors. It became evident, however, that such course outlines would rather closely reproduce those for the non-science majors. The material to be covered and the order of presentation would be much the same; the principal differences would be that for the science majors there need be no attempt to deemphasize the mathematics, and a reasonable knowledge of elementary physics could be assumed. This being true, the presentation becomes simpler for the instructor, and he can go into more detail in several areas and spend less time on some other areas such as the properties of light and radiation with which the students are familiar and probably only need a brief review. It appears unnecessary, therefore, to rewrite the outlines for the science-majors courses. The ones given for the non-science majors should serve satisfactorily for the most part, and the instructor should have no difficulty in changing the emphasis and the level of treatment to better match the background of the students. The notes as written are obviously aimed at the non-science majors courses, but it seems unnecessary to write another set to go with courses for science majors, and it is left for the instructor to translate the notes appropriately for the latter students.

The notes for the traditional course were prepared first and are extensive and, in some cases, detailed. Many of them apply as well to topics in the conceptual course outline, and all the notes are numbered serially to make it simpler to refer to them in either outline and also in the mini-course outlines where appropriate.

Not all Workshop participants would unanimously endorse all the opinions expressed in the notes, but the participants have checked the notes for factual accuracy, and hopefully no errors of fact have been overlooked as of the final revision date (early summer, 1975).

One of the main drawbacks to organizing courses along non-traditional lines is the absence of texts that parallel the course. It is far easier for both instructor and student when a good text is available and the course sticks fairly closely to the text. Perhaps in time one or more of the outlines presented here will encourage someone to write a text to fit, but for the present the absence of a text is a disadvantage that is hopefully outweighed by the pedagogical advantages of the new ways in which the material is organized. Frequent references to a number of modern texts are given in the notes. Some of these texts are standard introductory ones for courses in astronomy, and in those courses whose approach we have labeled "traditional" the standard introductions to astronomy will prove useful to both student and instructor. It is probable that the instructor will designate one of these as the principal text for the course, and even courses following the "conceptual" approach may well benefit from such a choice of text until one is written that more closely follows this approach. Besides these standard texts, references are made in the notes to other more advanced sources of material, more for the benefit of the instructor than the student, though not exclusively so. These are usually either texts or monographs on astrophysics or some sub-field such as stellar structure, cosmology, etc., and some are review papers such as those published in "Annual Reviews of Astronomy and Astrophysics", or the nine volume "Stars and Stellar Systems" set edited by Kuiper and Middlehurst. In a few cases references are made to published proceedings of topical conferences, and only occasionally is the instructor referred to the original literature. This hierarchy of references was adopted with the thought that the original literature is likely to be least accessible to the physicist in a school without an astronomy department and therefore in all likelihood without much in the way of library holdings of the astronomical literature. The texts and references chosen are far more likely to be available, and if not they are more easily and economically acquired than back issues of the Astrophysical Journal, for example.

There is always a large element of personal selectivity in references to texts rather than to original literature, particularly in references to general introductory texts of which there are quite a number extant, with the danger that some authors may feel theirs has been unfairly overlooked or slighted. Except for acknowledging the fact that our selectivity carries no intentional bias nor general qualitative endorsement, we attempt no apology for having singled out some parts of books we are familiar with as giving a particularly useful treatment of some particular topic for purposes of the course being annotated. Our purpose is to provide good guidelines for the instructor, not to endorse by reference or to condemn by omission any text or texts or other reference material.

In addition to the regular course outlines with notes that make up the main body of this document, the Workshop participants were asked to devise a series of "mini-courses" covering a variety of special topics in astrophysics. These mini-courses are of no well defined length except that they are generally intended to be presented in less than one school quarter, nominally considered to be about 28 class periods. Their lengths are flexible, but we envision them to run from perhaps half a dozen lectures up to perhaps 12 to 15, i.e. about half a quarter or a third of a semester. More than one can therefore be fitted into a quarter or a semester sequence. Alternatively, sequences running for two quarters or a full year can be made up of suitably related mini-courses, and several such sequences have been arranged around five different themes. Or the mini-courses can be given as part of another course whose main emphasis is not astrophysics; in this context they would be supplements to other physics courses illustrating applications of the physics to astrophysical problems. The flexibility in length of the mini-courses makes them well suited to this kind of use. Finally, these mini-courses may serve as guides to organization of seminars on astrophysical topics.

The mini-courses are designed for the most part for science students at the junior and senior levels, although a number of them could very well serve for graduate level use. They are not presented in as much detail as the regular course outlines, nor are they more than skeletally annotated. We hope in the near future to expand the mini-course outlines and to write a set of mini-texts to go with them in addition to a much fuller set of notes for the instructor. Meanwhile, the somewhat bare outlines are given here, and they should serve to indicate the usefulness of the mini-course concept in teaching interdisciplinary, topically oriented subject matter.

PART I

INTRODUCTION TO MODERN ASTROPHYSICS

for

Non-Science Majors
("Traditional" Approach)

I A. An Introduction to the Universe

Slide Show and descriptive commentary[1]

B. Simple Heliocentric Model of the Solar System

- 1) History of the heliocentric model[2]
  - (a) Early observational accuracy not capable of showing discrepancies in the Ptolemaic model.
  - (b) Copernicus and the advent of the heliocentric model[3]
  - (c) Tycho Brahe's observations, greatly improved accuracy-to better than a minute of arc by purely visual instruments[4]
  - (d) Kepler and the laws of planetary motion[5]
- 2) The modern picture
  - (a) Planets move about the sun in same direction in slightly elliptical orbits with Sun at one focus[6]
  - (b) All planetary orbits lie nearly in the same plane[7]
  - (c) The further from the Sun a planet is, the longer it takes to revolve once about the Sun in its orbit[8]
  - (d) Diurnal apparent motions[9]

C. Gravity

- 1) Basic concepts[10]
  - (a) Mass vs. weight[11]
  - (b) Gravitational attraction as a "force acting at a distance"[12]

(c) $F = GM/r^2$[13]

(1) the "g" at the Earth's surface and "weight".[14] The mass of the Earth

(2) the "g" at the Moons surface, at other planetary surfaces

(d) Simple circular orbits: balance between gravity and "centrifugal force"[15]

(1) the revolving ball-on-a-rubber cord analogy[16]

(e) Newton's laws of motion[17]

(f) Kepler's laws[18]

II Solar System (major members)

A. The terrestrial planets and the Moon

1) Their names, orbital radii, periods, sizes, densities, compositions[19]

2) Cratering[20]

3) Planetary atmospheres[21]

(a) Atmospheric retention[22]

(b) "Greenhouse" effect[23]

B. The Jovian planets[24]

1) Names, orbital radii, periods, etc.

2) Contrast in intrinsic properties between terrestral and Jovian

3) Special features:

(a) Jupiter red spot, radio emission, clouds and winds, rapid rotation, nearly a sun[25]

(b) Saturn rings

(c) Many moons of some of these planets

C) Planetary temperatures[26]

1) Radiation balance determines temperatures

(a) Inverse square law

(b) T^4 law

(c) Reflectivity (albedo)

2) Interior sources of heat in planets

(a) Radioactivity[27]

(b) Tidal friction[28]

III Stars

A. Properties of light and radiation[29]

1) Frequency, wavelength, speed of light, and $f\lambda = c$

(a) Wave and particle properties of light. The photon. $E = hf$

(b) Electromagnetic spectrum

(1) General regions of spectrum from gamma rays to VLF radio waves and 60 Hz power line radiation[30]

(2) Atmospheric "windows" and the value of space observatories[31]

(c) Doppler effect[32]

(d) The light year[33]

2) Thermal radiation[34]

(a) Stefan-Boltzman law, $E \propto T^4$

(b) Wien displacement law $\lambda_{max}T$ = constant

(c) Planck's law. Planck's constant and the quantum. $E = hf$

3) Absorption and scattering of light[35]

B. The Sun as a star

1) Visual appearance, Photosphere[36]

(a) Gaseous nature of photosphere

(b) Limb darkening and reddening. Scattering of light in the Sun's atmosphere

(c) Detailed appearance of the photosphere--granulation

(d) Other parts of Sun's atmosphere: chromosphere and corona

(e) Dynamic events in the Sun's atmosphere: prominences, flares, the solar wind[37]

2) Gross properties: M, R, L, Teff, composition, density (mean and central), central temperature and pressure[38]

3) Solar energy source problem[39]

(a) Gravitational contraction would energize the sun for only 10^7 years

(b) Age of sun at least equals the age of the earth which is $\sim$4.6 billion years

(c) Estimates of total solar radiation over $\sim$4 billion years imply that only nuclear energy can provide that much energy

C. Properties of stars[40]

1) Distance measurement[41]

(a) By triangulation. Parallax

(b) By apparent brightness. Photometric distances[42]

(1) Common stars

(2) Unusual stars[43]

2) Intrinsic properties

(a) Luminosity[44]

(b) Color and temperature[45]

        (1) Spectral classes
    (c) Radius from luminosity and temperature[46]
    (d) Mass[47]
    (e) Composition[48]
    (f) Range of values of L, M, R, T[49]
3) Spectra[50]
    (a) Emission and absorption as energy level changes in atoms[51]
    (b) Ions, ionization, excitation[52]
        (1) Spectral sequence and temperature/color[53]
        (2) Luminosity class[54]
        (3) Abundances[55]
4) H-R diagram[56]
    (a) Concept of correlation diagrams[57]
    (b) Stars with same age and initial compositions
        (1) Galactic clusters
        (2) Globular clusters
    (c) Nearby stars[58]
        (1) Selection effects
        (2) Rudiments of Main Sequence
    (d) General field stars
        (1) Main sequence
        (2) Giants, variables, white dwarfs, Hertzsprung gap, planetary nebulae, etc.
    (e) Stellar masses from binaries[59]
    (f) Use of the diagram to measure distances[60]
        (1) Main sequence matching
        (2) Spectroscopic parallax

D. Stellar Structure

- 1) Main sequence stars (Sun as prime example)
  - (a) Nuclear energy source
    - (1) $E = mc^2$ from relativity
    - (2) 4H→He + energy[61]
      - (i) 0.7% of mass→energy in this reaction
      - (ii) Need high temperature and density[62]
  - (b) Hydrostatic equilibrium
    - (1) Gravity vs. density gradient[63]
    - (2) Radiation pressure[64]
  - (c) Energy transport[65]
    - (1) Radiative[66]
      - (i) Temperature gradiant
      - (ii) Radiation pressure
    - (2) Convective[67]
    - (3) Conductive[68]
      - (i) Importance in some special stars
  - (d) Models of stellar interiors[69]
    - (1) Upper main sequence[70]
    - (2) Lower main sequence[71]
- 2) Evolution[72]
  - (a) Necessity for star to change with time[73]
  - (b) Mass-luminosity relation[74]
  - (c) Evolutionary tracks on H-R diagram[75]
    - (1) Galactic clusters
    - (2) Globular clusters
    - (3) "Turn-off" point as a measure of age[75a]

- (d) Pre-main sequence, star formation[76]
    - (1) In gaseous, dusty regions[77]
    - (2) Gravitational energy role[78]
    - (3) Time scale $\sim 10^7$ years[79]
    - (4) H-R track[80]
    - (5) Onset of nuclear reactions[81]
- (e) Main sequence
    - (1) "Zero age" main sequence[82]
    - (2) H-R track[83]
    - (3) Time scale for nuclear burning $\sim 10^{10}$ yr.[84]
    - (4) Upper and lower main sequence stars[85]
- (f) Post-main sequence[86]
    - (1) Role of gravity as nuclear fuel is exhausted[87]
    - (2) Shell burning and shell structure[88]
    - (3) He flash, core changes[89]
    - (4) H-R tracks to red giant stage[90]
    - (5) Triple alpha process and carbon burning in red giants[91]
    - (6) Differences between UMS and LMS late evolution[92]
    - (7) Very low mass "black dwarfs"[93]
- (g) Post-red giant evolution
    - (1) Complications, short time scale left-right H-R tracks, Hertzsprung gap[94]
    - (2) Variable stars and novae[95]
- (h) Terminal stages of not too massive stars (e.g., Sun)

  - (1) Chandrasekhar limit: $1.4\ M_\odot$ and core rigidity, degeneracy[96]
  - (2) White dwarf
    - (i) Structure
    - (ii) Cooling time
    - (iii) Masses (theory, measurement)[97]
  - (3) Planetary nebulae[98]
    - (i) Mass ejection
- (i) Violent death of massive stars[99]
  - (1) Higher temperatures and pressures lead to heavy element production to Fe^{56}
  - (2) Collapse due to neutrino loss from core[100]
    - (i) Short time scale
    - (ii) Energy released[101]
    - (iii) Shock wave and neutrino blast ejection of material from star[102]
    - (iv) Very heavy element production and dispersion[103]
    - (v) Neutron star residue[104]
      - (1) Properties[105]
  - (3) Observational aspects of supernovae[106]
    - (i) Light curves
    - (ii) Peak luminosities
    - (iii) Frequencies of occurrence
    - (iv) Remnants (e.g., Crab)[107]

(iv) Remnants (e.g., Crab)[107] (cont.)

- (1) Radiation: γ-rays to radio waves
  - (a) Synchrotron radiation[108]
    - (i) Recognizable by spectrum, polarization
    - (ii) Implies high energy (relativistic) Particles in magnetic fields
- (2) Matter ejection[109]
  - (a) Velocities, time since explosion
- (3) Pulsar[110]
  - (a) Rapidly rotating neutron star; conservation of angular momentum
  - (b) Strong magnetic field; conservation of magnetic flux
  - (c) "Lighthouse" effect gives precise radiation pulses
  - (d) Slowing down measures energy loss by radiation
- (4) Heavy element enrichment of interstellar medium[111]
  - (a) Raw material for new generation of stars
    - (i) Different initial composition so diferent properties
    - (ii) Different spectra, different evolution

(j) Black holes[112]

- (1) Mass too great for nuclear matter to support
- (2) Properties: light bent back, no communication with outside world
  - (i) Two observers one outside, one entering--different appearance
  - (ii) Detection by gravitational effects. Is Cygnus X-1 a black hole?

IV The Milky Way Galaxy--a survey[113]

1) General distribution of objects: stars, clusters, gas, dust, nucleus, arms, Sun

    (a) Our position

        (i) Problems of seeing the Galaxy from our position[114]

            (1) Dust--extinction and reddening

            (2) Observation of nucleus and beyond

    (b) Distance measurements[115]

        (i) Cluster parallax--Main Sequence fitting

        (ii) Cepheids and RR Lyrae measures

        (iii) Size of Galaxy, position of Sun

2) Slide Show II: Orion, Pleides, Horseshoe, Trifid, North American Nebulae, Sombrero Galaxy, etc.[116]

3) Galactic rotation. Mass of Galaxy[117]

4) Similarity to external spiral galaxies (e.g., M31)[118]

    (a) spiral arms, dust

    (b) 21-cm radio observations of H distribution[119]

    (c) Superimposed maps of stars and hydrogen distribution

5) Stellar populations I and II[120]

    (a) Distribution differences

    (b) Chemical differences

    (c) Age differences

    (d) Motion differences

    (e) Correlation of Pop. I with dust and gas

6) Nucleus[121]

    (a) Mass, star density, star types, size

    (b) Radio and infrared emission

    (c) Activity--energetic events, jet ejection

7) Evolution[122]
    (a) Age of oldest stars
    (b) Color of nucleus as a measure of age
    (c) Shape vs. age

V Galaxies in general
  1) Distance scales, distance measurement[123]
    (a) Cepheids
    (b) Novae and Supernonae
    (c) Form vs. integrated brightness and size[124]
    (d) Red shift[125]
  2) Hubble's law[126]
    (a) Red shift calibrated by other methods out to $Z \sim 0.4$[127]
    (b) Looking back in time[128]
    (c) Larger red shifts ($z > .1$: QSO's)[129]
  3) Galactic Morphology[130]
    (a) Basic shapes
    (b) Old ideas about evolution of shapes
    (c) New ideas about evolution[131]
  4) Clusters of galaxies[132]
    (a) Local Group
    (b) Other prominent clusters (Stephan Quintet, Fornax I, Virgo, Corona Borealis clusters)
    (c) Superclusters
    (d) Related galaxies[133]
      (i) Galactic bridges
      (ii) Spatial alignments
      (iii) Discordant redshifts

VI Cosmology[134]

1) Expanding Universe
    (a) Hubble's law time scale
    (b) Relativity
    (c) 3 dimensional analogies[135]
    (d) Big Bang
        (1) Element and Galaxy formation[136]
        (2) 3°K background radiation[137]
    (e) Steady State
        (1) Continuous creation[138]
        (2) No difference in galaxy counts with time.
2) Cosmological principle
    (a) No preferred vantage point
    (b) Curved space a necessary consequence[139]
3) Infinite expansion vs. oscillating universe[140]
    (a) Determined by Hubble constant and density
        (1) Explosive force vs. gravity
        (2) Estimated critical density for oscillation
4) Observational cosmology[141]
    (a) Velocity vs. distance
    (b) Galaxy counts[142]
    (c) Radio source counts
    (d) Missing mass problem[143]
        (1) Present density implies infinite expansion
    (e) 3°K background radiation[144]
    (f) Early element formation and the He excess problem[145]

5) QSO's, Radio Galaxies, Active Nuclei[196]

   (a) Large red shifts imply great distances

      (1) The red shift controversy--Doppler or gravitational

         (i) Gravitational redshift

   (b) Large energy emission

   (c) Small source sizes

      (1) Variability time scale related to source size (coherence)[147]

   (d) Large energy densities

   (e) Violent events[148]

      (1) Jets and explosions in galactic nuclei

      (2) Double radio sources[149]

         (i) Optical galaxy lies between radio sources

      (3) Colliding galaxies

         (i) Frequency vs. star collision frequency

         (ii) Gas and dust in galactic collisions

      (4) Some theories about violent events[150]

         (i) Supernova chain reactions

         (ii) Black hole formation and accretion

         (iii) White holes, warm holes.

VII Life in the Universe[151]

1) Cosmogony--formation of planetary systems

   (a) Frequency[152]

   (b) Angular momentum--the slowly rotating stars

   (c) "Zone of life"[153]

(d) Observation of other planetary systems[154]

  (i) Difficulties

  (ii) Barnard's star orbital peculariarities

(e) Chemical evidence

  (i) Complex molecules in interstellar medium and comets (meteorites)

  (ii) Laboratory evidence for buildup of complex molecules[155]

(f) "Statistics of life"[156]

  (i) Factors in estimating probability of finding extraterestrial life

  (ii) Resultant estimate of 10^{11} other life bearing planets in Universe

(g) Communication and travel[157]

  (i) Times required

  (ii) Energy required

  (iii) Space-time travel

Suggested Time Schedule for "Traditional" Course
for Non-Science Majors

(Note: Sections below are labeled as in the course outline. Numbers refer to days of instruction)

	Semester Course	Quarter Course
(I) A	1	1
B	1 1/2	1
C	1	1
(II) A	1	1
B	2	1
C	1 1/2	1 1/2
(III) A	2	2
B	1 1/2	1
C 1	1	1/2
C 2	1 1/2	1
C 3	1	1/2
C 4	2	1 1/2
D 1	2 1/2	2
D 2 a,b,c	1	1
D 2 d,e	1 1/2	1
D 2 f,g	1	1/2
D 2 i	2	1
D 2 j	1	1/2
(IV)	3 1/2	3
(V)	2 1/2	2
(VI)	4	3
(VII)	2	1
	38 days	28 days

PART II

INTRODUCTION TO MODERN ASTROPHYSICS

for

Non-Science Majors
("Conceptual" Approach)

I. Introduction to the Universe

- (1) Pictorial survey(1)
- (2) Principal themes and objectives(159)
  - (a) Form, Scale, Structure of the Universe
  - (b) Gravity and its consequences on various scales
  - (c) Light and radiation
  - (d) Gas laws and large scale random motions. Elements of stellar structure.
  - (e) Nuclear processes and stellar energy. Stellar evolution.
  - (f) High energy astrophysical processes. Cosmic rays, neutrino astronomy, X-ray and gamma ray astronomy, the "Big Bang" cosmology, etc.

II. Form, Structure, and Scale of the Astronomical Universe

- (1) Distance of Sun(160)
  - (a) Trigonometric measurement
  - (b) Radar measurement(161)
- (2) Distances of stars(41)
  - (a) Hypothesis that stars are suns(162)
  - (b) Inverse square law(42): apparent brightness $\propto r^{-2}$
    - (i) Apparent brightness vs. intrinsic brightness (luminosity)(44)

(ii) Apparent luminosity as a distance measure for stars, clusters, galaxies.

(α) Applications

(1) Mean separation between stars(163)

(2) Size and form of Milky Way(113)

(c) Trigonometric distance measurement. Parallax

(i) Test of hypothesis that stars are suns.(164)

(d) Binary stars(165)

(i) Illustrate spread in absolute luminosities

(a) Complicates use of inverse square law

(b) Calls for classification of intrinsic luminosity in terms of other physical parameters

(e) Stellar classification

(i) Originally empirical in terms of color(45,166)

(α) Methods of photometry: visual, photographic, photoelectric.(167)

(β) Purpose of photometry: to measure spectral distribution

(ii) Color is related to surface temperature

(α) Temperature is the important physical parameter.(168)

(β) Radiative laws show luminosity proportional to T^4

(iii) Result of L-C classification: H-R diagram(56-58) (α) Main features of H-R diagram

(β) Use of diagram to measure distance (spectroscopic parallax) (60)

(3) Distances and sizes of galaxies

(a) Galaxies as large systems of stars (Hypothesis: galaxies are Milky Ways) (113,114)

(i) Closer, smaller star systems (clusters)

(α) Methods of distance measurements for clusters

(β) Extension to nearby galaxies, mainly $L \propto r^{-2}$ for stars

(ii) Distance measurements of distant galaxies (115)

(α) Use of variables (cepheids, novae, supernovae, etc.)

(β) More exotic methods: redshift, size classification, brightest clusters, etc.

(b) Variations in size, form, luminosity, color (123)

(i) Expected from differences in number and types of stars.

(ii) Form classifications (Hubble and modern) (130)

(4) Clusters of galaxies (sizes and distances) (132)

(a) Hypothesis: brightest galaxy in a cluster is a "standard candle" (169)

(b) Red shift as distance measure. (115)

(i) Hubble's law (126)

(c) Principle of Uniformity of the Universe

- (i) Observational basis (superclusters, radio astronomy results, 3°K radiation,(144) galaxy counts(142)
- (ii) Cosmological consequences(139)
- (iii) Missing mass and stability of the Universe(143)

(d) Classification of galaxies:(130) evolution of galaxies(131)

III. Gravitation.

- (1) Gravity and gravitation: historical(2-5)
- (2) Basic concepts(10)
  - (a) Speed, velocity, acceleration: space-time diagrams(170)
  - (b) Relativity of motion (Galilean relativity)(171)
  - (c) Mass and weight(11)
  - (d) Gravitation as a force acting at a distance(12)
  - (e) $F = GMm/r^2$ (13)
    - (i) the "g" at Earth's surface.(14) The mass of the Earth
    - (ii) "g" at the Moon's surface; at other planet's surfaces.
  - (f) Simple circular orbits: balance between gravity and "centrifugal force"(15)
  - (g) Newton's laws of motion(17)
  - (h) Kepler's laws(18)
  - (i) Conservation of energy(172)

(3) Motion of satellites
(a) Earth-moon system
(b) Jupiter's moons
(c) Artificial satellites
(4) Non-circular orbits(174)
(a) Elliptic orbits
(b) Hyperbolic and parabolic orbits
(i) Binding energy
(ii) Escape velocity
(c) Prediction from Kepler's and Newton's laws(175)
(5) Solar system orbits(176)
(6) Binary stars(177)
(a) Means of obtaining mass and thereby the mass-luminosity relation(178)
(7) Radial velocities through Doppler shift
(a) Wave nature of light(29-31)
(b) Spectral lines(50-52)
(c) Doppler shift(32)
(i) Use in astronomy to measure radial velocities of everything from planets to distant galaxies and the expansion of the Universe
(ii) Interpretation of the red shifts of distant galaxies as Doppler shifts
(8) Dynamics of star clusters and systems of galaxies(179)
(a) Swarms, random motions

        - (b) Disks
            - (i) Rotation
            - (ii) Flattening
        - (c) two population concept
    - (9) Cosmic Expansion, extragalactic motions(134)
        - (a) Distance scales and distance measurements(124)
        - (b) Red shift and Hubble's law(126,127)
        - (c) Interpretation of Principle of Uniformity(139,144)
        - (d) Quasi-stellar objects(146,147)
        - (e) Age of the Universe
            - (i) Inverse Hubble time(126)
            - (ii) Age of solar system(180)
            - (iii) Ages of old elliptic clusters.(181)
- IV. Evolution of stars and Stellar Structure
    - (1) Main sequence stars (Sun as prime example)
        - (a) Nuclear energy source
            - (1) $E = mc^2$ from relativity
            - (2) $4H \rightarrow He$ + energy[61]
                - (i) 0.7% of mass→energy in this reaction
                - (ii) Need high temperature and density[62]
        - (b) Hydrostatic equilibrium
            - (1) Gravity vs. density gradient[63]
            - (2) Radiation pressure[64]

- (c) Energy transport 65
  - (1) Radiative[66]
    - (i) Temperature gradiant
    - (ii) Radiation pressure
  - (2) Convective[67]
  - (3) Conductive[68]
    - (i) Importance in some special stars
- (d) Models of stellar interiors[69]
  - (1) Upper main sequence[70]
  - (2) Lower main sequence[71]

(2) Evolution[72]

- (a) Necessity for star to change with time[73]
- (b) Mass-luminosity relation[74]
- (c) Evolutionary tracks on H-R diagram[75]
  - (1) Galactic clusters
  - (2) Globular clusters
  - (3) "Turn-off" point as a measure of age[75a]
- (d) Pre-main sequence, star formation[76]
  - (1) In gaseous, dusty regions[77]
  - (2) Gravitational energy role[78]
  - (3) Time scale $\sim 10^7$ years[79]
  - (4) H-R track[80]
  - (5) Onset of nuclear reactions[81]

(e) Main sequence

- (1) "Zero age" main sequence[82]
- (2) H-R track[83]
- (3) Time scale for nuclear burning $\sim 10^{10}$ yr.[84]
- (4) Upper and lower main sequence stars[85]

(f) Post-main sequence[86]

- (1) Role of gravity as nuclear fuel is exhausted[87]
- (2) Shell burning and shell structure[88]
- (3) He flash, core changes[89]
- (4) H-R tracks to red giant stage[90]
- (5) Triple alpha process and carbon burning in red giants[91]
- (6) Differences between UMS and LMS late evolution[92]
- (7) Very low mass "black dwarfs"[93]

(g) Post-red giant evolution

- (1) Complications, short time scale left-right H-R tracks, Hertzsprung gap[94]
- (2) Variable stars and novae[95]

(h) Terminal stages of not too massive stars (e.g., Sun)

- (1) Chandrasekhar limit: 1.4 $M_\odot$ and core rigidity, degeneracy[96]
- (2) White dwarf
  - (i) Structure
  - (ii) Cooling time
  - (iii) Masses (theory, measurement)[97]

- (3) Planetary nebulae[98]
  - (i) Mass ejection
- (i) Violent death of massive stars[99]
  - (1) Higher temperatures and pressures lead to heavy element production to Fe^{56}
  - (2) Collapse due to neutrino loss from core[100]
    - (i) Short time scale
    - (ii) Energy released[101]
    - (iii) Shock wave and neutrino blast ejection of material from star[102]
    - (iv) Very heavy element production and dispersion[103]
    - (v) Neutron star residue[104]
      - (1) Properties[105]
  - (3) Observational aspects of supernovae[106]
    - (i) Light curves
    - (ii) Peak luminosities
    - (iii) Frequencies of occurrence
    - (iv) Remnants (e.g., Crab)[107]
      - (1) Radiation: γ-rays to radio waves
        - (a) Synchrotron radiation[108]
          - (i) Recognizable by spectrum, polarization
          - (ii) Implies high energy (relativistic) Particles in magnetic fields
      - (2) Matter ejection[109]
        - (a) Velocities, time since explosion

- (3) Pulsar[110]
  - (a) Rapidly rotating neutron star; conservation of angular momentum
  - (b) Strong magnetic field; conservation of magnetic flux
  - (c) "Lighthouse" effect gives precise radiation pulses
  - (d) Slowing down measures energy loss by radiation
- (4) Heavy element enrichment of interstellar medium[111]
  - (a) Raw material for new generation of stars
    - (i) Different initial composition so different properties
    - (ii) Different spectra, different evolution

(j) Black holes[112]

- (1) Mass too great for nuclear matter to support
- (2) Properties: light bent back, no communication with outside world
  - (i) Two observers one outside, one entering--different appearance
  - (ii) Detection by gravitational effects. Is Cygnus X-1 a black hole?

Suggested Time Schedule for "Conceptual" Course for Non-Science Majors

(Note: Sections below are labeled as in the course outline. Numbers refer to days of instruction)

		Semester Course	Quarter Course
(I)	1	1	1
	2	2	1 1/2
(II)	1,2 (a)-(c)	2	1 1/2
	2 (d), (e)	2	1 1/2
	3	2	1 1/2
	4	2	1 1/2
(III)	1,2	3	2
	3-6	2	1 1/2
	7-9	2	1 1/2
(IV)	1	3	2
	2 (a)-(c)	3	2
	2 (d), (e)	3	3
	2 (f), (g)	3	2
	2 (h)	2	1 1/2
	2 (i)	3 1/2	2 1/2
	2 (j)	2 1/2	1 1/2
		38 days	28 days

NOTES AND COMMENTS ON COURSE OUTLINES

1. "Slide Show" notes on this and subsequent slide shows will be found in Appendix A.
2. Fred Hoyle ["Astronomy," Doubleday & Co., N. Y. (1962), Ch. 3 and 4] gives an excellent review of this subject. In particular, he gives an excellent discussion of the Earth-centered (Ptolemaic) vs heliocentric points of view and the way in which the epicyclic picture was devised to account for early observations (pp. 71-74 and 89-91). It is not advisable to go into details as Hoyle does but simply to show students that the ancients weren't really so näive in their belief in an Earth-centered universe; such a system fitted their observations perfectly well. It was only when observational accuracies of a few minutes of arc (the famous 8 minute discrepency in Mars' orbit by Tycho Brahe's observations that led Kepler beyond the corrected Copernican theory-see Hoyle p. 116) that it was possible to show that the Earth-centered theories did not agree with experiment.

   This is a good place to emphasize the interplay between theory and experiment in physical science, bringing in the points that a theory is only good if it can be tested against experiment and observation, that history has shown that each advance in experimental or observational techniques has led to more and better data revealing limitations of existing theory and giving new facts that better theories must account for, etc. Students at this level are generally strangers to the whole concept that there is nothing sacred about theory, that theories are all rather like trial balloons: fair game to be shot down by the observed facts, that this halting, stepwise progression is how man has learned what he knows about nature, that this is the real crux of the "scientific method" and not the imagined neat, logical sequence of observation, deduction, and generalization often mislabeled the scientific method by non-scientists.

3. Hoyle, Ch. 4, and especially pp. 96-98, gives a convincing speculation as to the thinking that may have led Copernicus to adopt the heliocentric idea.
4. A good verbal portrait of Tycho, his life and times, is given by Arthur Koestler in "The Watershed," Doubleday Anchor, N.Y., (1960), Ch. 4. This is a well-known biography of Kepler and is highly recommended to the layman as an excellent description of the history of the crucial 17th century turning point in astronomy and, in fact, of modern physical science.
5. Mention the 8 arc-minute discrepancy in the Martian orbit between the predictions of the Copernican model (heliocentric but with epicyclic motions of the planets revolving about the Earth as center--See Hoyle, also Koestler). Don't present the laws themselves yet. Wait until the next section on gravity.
6. The chief properties of an ellipse should be explained qualitatively: minor and major axes, foci, eccentricity. The small eccentricity of all orbits except the innermost (Mercury) and outermost (Pluto) should be mentioned; the orbits except for these two are really quite close to being circular.

7. All standard astronomy texts have tables of the features of the planetary orbits. The inclinations range from 7° to 0.8° with respect to the Earth's orbit except for Pluto whose orbit is inclined at 17°. Pluto is generally a maverick lending support to the idea that it was not formed at the same time or by the same process as the other eight planets.

8. It should be pointed out that this forerunner of Kepler's second and third laws accounts (qualitatively) for the main anomalous apparent motions of the planets as seen from the Earth (e.g., the retrograde motion of Mars). This is a good point at which to explain the apparent motions of the planets seen from Earth. A series of plan views of the solar system at successive times is a good teaching aid. There is also a mechanical device called an Orrery which has several planets on wire arms that rotate about the central sun at correct relative speeds. This is especially useful for smaller classes. It is available as Cat. No. 70, 374 from American Science Center, Inc., 5700 Northwest Highway, Chicago, 60646, for about $16.

9. Show both the apparent motions from the daily rotation of the Earth and the smaller effect on the times of rising and setting of the fixed stars due to the annual revolution about the sun. The ecliptic can be defined here.

10. It seems a little presumptuous to make suggestions to a physicist about teaching gravity, Newton's laws, etc., and the following

suggestions are mainly in the nature of reminders about the physical naivete of the majority of students who will be taking this course. Most physicists have never been called upon to teach this group of students and they are generally shocked to find how much they take for granted through long association that is really not a familiar concept at all for the humanities student. The greatest care and pedagogical skill has to be employed not to lose the student here and again at the following "little physics lessons" that alternate with the astronomical sections throughout the first part of this course.

11. Mass is not a familiar concept to many students who have not had physics in high school. The idea that mass and weight are quite different things needs to be introduced here.

12. The concept of a force acting at a distance is also foreign to many students without physics backgrounds. Magnetic forces are perhaps the most familiar examples to the student, though of course electrostatics is the best introductory analogy to gravity.

13. Use judgement about writing formulas, even this simple, for these students. Introduction of the salient points via proportion with words and simple examples is generally more successful. Try to convince the student that he can really understand the phenomena without plugging numbers into a formula. If you display the formula, play down its role in understanding the concept of gravitational force.

14. The gravitational acceleration is probably a good point at which to slip in Newton's second law, but it need not be mentioned by name yet. In fact, you have probably already paved the way in distinguishing between weight and mass. This is also a good place to reiterate that distinction.

15. Since "centrifugal force" is such a familiar idea, it is used here initially without introducing the physically correct way of looking at circular motion. See (17) below.

16. This analogy is good in that it illustrates in familiar terms the establishment of different equilibrium orbital radii. With it, the concept of equilibrium between the central force, gravity, and the "centrifugal force" is easy to get across. But the analogy can be misleading to a bright student because the elastic central force doesn't give a relation between period and orbital size anything like that of Kepler's third law.

17. Now the idea of centripetal acceleration to produce curvilinear motion can be introduced in conjunction with Newton's first law and centripetal force in conjunction with his second law. Gravitational acceleration, "g", can also be discussed here as GM/R^2 arising from Newton's second law. But again use caution about writing formulas.

18. It is all right to show that Kepler's laws are contained in Newton's. But be sure to emphasize that Kepler's laws came first and were laboriously arrived at as a means of accounting

for the observed orbit of Mars. Acknowledge Newton's debt to Kepler but point out the great generalization that Newton invoked.

19. See data in any standard astronomy book. Only use rough values for orbital radii and periods, just to give the student a qualitative picture of the geography of the inner solar system. Avoid all finer details such as orbital inclinations, eccentricities, etc. Likewise give planetary radii in terms of Earth radii, rounded off. Explain how densities are determined, i.e., how masses are gotten by Kepler's third law from observed periods and these with directly observed planetary radii give mean densities. Show how these give some idea about composition even though the planets may be very inhomogeneous. Use this example to show the kind of reasoning plus observation plus natural law by which a deduction can be made about a property of an astronomical object that is not directly observable.

20. Show illustrations of lunar and Martian cratering from NASA flights. A recent lunar globe is good for small classes (Cat. No. 70, 515, Edmund Scientific Co., Barrington, N.J. 08007, about $14.00). Mention impact and volcanic cratering as indicators of earlier conditions and of molten core. Mention recent findings by space probe that Mercury is heavily cratered, too. Show pictures of some of the more striking lunar craters such as Tycho and the Martian Nix Olympica crater. Mention two chief origins: volcanic and impact.

The National Geographic Society has published an excellent map of Mars (Feb., 1973) and there is a recent series of articles in Science beginning with the November 22, 1974 issue that is quite up to date as a review of solar system studies.

21. Again the standard texts give the densities, temperatures, and compositions. Don't dwell on details, just give a broad brush picture, mainly to show ranges of ρ, T, composition.

22. Describe qualitatively in terms of competition between escape due to thermal motion of molecules and gravitational attraction. This is where a little kinetic theory can be introduced, but qualitatively try to get across the idea that temperature is a measure of molecular kinetic energy and velocity. Give order of magnitude of molecular speeds in familiar units (e. g., relate to speed of sound). Explain that lighter gas molecules move faster at given T than heavier ones and are less held back by gravity so are more readily lost into space. Explain that a certain relation between gas molecular weight, atmosphere temperature, and mass of the planet must be obeyed for that gas to be retained.

23. A lot of radiation physics is involved here but remember that such terms as wavelength of light, infrared radiation, molecular absorption, etc., are probably foreign to most of these students. The radiant heat from the sun is familiar enough, but the concept that the Earth re-radiates at longer wavelengths that are not transmitted by the atmosphere needs

careful presentation in terms of every-day observations.

24. The principal features of these planets are found in standard texts. Again relatively little detail need be presented. The important thing to stress is that the Jovian planets are essentially different from the terrestrial ones and that the different properties of these two groups of planets must be accounted for in any satisfactory theory of the formation of the solar system.

25. Jupiter would be a self-luminous star in its own right if it were about 100 times as massive as it is. It's mass is about 10^{-3} solar masses and the least massive true stars have about 0.1 solar masses. To put it more strikingly, if it were only about 5 times larger in diameter, it would be a star. Actually, it does emit more radiation than it receives and, strictly speaking, is self-luminous. It might therefore claim to be a star as much as a "black dwarf" whose mass is insufficient to initiate nuclear fusion, but this is nit-picking.

26. These are equivalent black body temperatures of the surface or the upper atmospheres for planets like Venus with opaque atmospheres. The concepts of thermal radiation, inverse square law, and radiative equilibrium are all introduced here. Experiments to demonstrate the inverse square law and possibly also the T^4 law may be appropriate though the latter may involve rather elaborate apparatus for a lecture demonstration.

27. The idea that 'heat results from' radioactive decay, actually from the stopping of the decay products, will be new to most students. In fact, the concept of radioactive decay itself

may be hazy to many of these students. Perhaps it should be mentioned that decay cannot be hurried and there is the resultant problem with reactor wastes.

28. The best approach here is probably the idea that the tidal currents generate heat by friction. In a semester course there may be time to explain tidal action in more detail. See standard texts. Heat generation in tidally distorted solid bodies, not just through ocean tides, can also be explained qualitatively.

29. Try to avoid presenting this material as a "Physics Lesson". Be as qualitative as possible; use familiar analogies (e.g., water waves to describe wavelength, frequency, etc.) use drawings, slides, graphic materials wherever possible. Several modern astronomy and introductory physics texts have good illustrations that could be used as slides. It may even be advisable to use f for frequency instead of ν, though λ is so universal its use may be justified. Again, a caution against formulae and quantitative presentation--try to get across the fundamental idea rather than the mathematical formulation, even when very simple.

30. A good picture of the spectrum on a logarithmic scale is helpful. A serviceable though simple one (without a wavelength scale) is given by Inglis, ["Planets, Stars, and Galaxies" 2nd Ed., John Wiley & Soms, N.Y. (1967), p. 41]. A beautiful color plate of the visible spectrum together with

sample spectra of three principle kinds of spectra is given facing p. 486 in L. Rudaux and G. deVaucouleurs, ["Larousse Encyclopedia of Astronomy," Prometheus Press, N. Y. (1959)]. R. Jastrow and M. H. Thompson, ["Astronomy: Fundamentals and Frontiers," 2nd Ed., Wiley & Sons, N. Y., 1974, p. 30] has a good figure of the electromagnetic spectrum.

31. Emphasize two advantages of space astronomy: the capability to see in important regions of the spectrum, especially in the far ultraviolet and infrared, and the absence of atmospheric turbulence, the "seeing" limitation, permitting great increases in resolution to near diffraction limits. This not only permits better angular resolution than before, but stellar objects are imaged onto smaller areas of detectors, and for detectors that are flux sensitive such as the photographic plate, this flux enhancement at the receiver increases the sensitivity of the telescope for detection of faint objects. Also, small detectors have less noise. This is a good place to show practical things limit observations.

32. The familiar train whistle example is useful here; however, in discussing the effect quantitatively, be careful to avoid any reference to the medium in which waves propagate. The acoustical analogy contains a pitfall here. One can simply say that if an observer and source are at rest relative to each other, the observer receives c/λ light waves each second. If the source and observer are in relative motion with

velocity v, then the observer receives an additional $\pm v/\lambda$ waves per second so the apparent frequency would be $\frac{c\pm v}{\lambda} = f_o(1\pm\frac{v}{c})$. This is easier to visualize if the source emits short flashes of light rather than sine waves, one flash per light wave. It is probably best for these students just to introduce the effect qualitatively using the acoustical anology and say that the result is that for relative source velocities not too near the speed of light the wavelength is shifted by an amount proportional to v/c. Introduce the terms red shift and blue shift for receeding and approaching objects, note how small the effect is even for objects moving as fast as 1000 km/sec (translate into miles/sec.) which is a respectable relative speed in astronomy, except for distant galaxies, and point out that the Doppler effect provides astronomers with one of their most valuable tools to study stellar motion. Note also that a fairly high resolution spectrograph must be used on the telescope to measure Doppler shifts. A simple experiment to illustrate the Doppler effect is to tie a toy reed whistle to a string. Attach a set of paper fins to the whistle so it will "fly" head first, and whirl it about in a circle. The pitch variation will be quite evident.

33. Present this as a handy way to talk about the large distances in astronomy. Give some of the usual correspondences: the Sun is ~ 8 1/3 light-minutes away, the outermost planet,

Pluto, is 5 1/2 light-hours from the Sun, the nearest star, Proxima Centauri, is about 4 1/4 light years away, the center of our Galaxy is about 30,000 light years, the nearest galaxy, the Large Magellanic Cloud, is about 160,000 ly, and so on. A year is about 3.15 x 10^7 sec. and with c = 186,000 mi/sec, a light year is a little less than 6 x 10^{12} miles. Exponential notation can be introduced here. Write out 6 x 10^{12} = 6,000,000,000,000 and name it: 6 thousand trillion miles to a light year. Convince the student of its magnitude (it is about 250 million trips around the world at the equator) and its utility in dealing with large distances.

This is also a good point at which to review powers of ten notation.

34. The Stefan-Boltzmann law is best presented at this level as simply a relation that accounts for the observations. Describe the basic experiment: source, source temperature measurement, and radiation detector, and the result $E \propto T^4$. The absolute temperature must be introduced, of course, but even this can be done in terms of the experiment: if the detector response is plotted as a function of the 4th power of temperature measured on the "wrong" scale, say °F, then the curve will only be a straight line if one adds 459°F to the source thermometer reading, or 273° to the thermometer if it reads °C. This establishes a new temperature scale whose zero is very cold (-273°C, -459°F) but this temperature

scale seems to be the right one to use in many areas of physics and chemistry besides thermal radiation. This kind of presentation seems to be right for most students at the level of this class.

The Wien displacement law can likewise be given as a relation that agrees quantitatively with the qualitative observation that cooler objects are redder than hotter objects and that very hot objects appear white-hot or even bluish. Relate this to colors of stars. Most students have probably never noticed that stars vary in color. This is a good place to mention such things as red giants, white dwarfs, blue supergiants, yellow dwarfs as having in their very names a clue to their surface temperatures. The Sun is a yellow star with surface temperature just under 6000°K (about 4 times the melting point of iron): a red giant may typically have a temperature around 4000°K, a white dwarf around 10-15,000°K, and the young blue stars may be as hot as 50,000°K. "The hotter, the brighter, the bluer" is a good mnemonic.

Regarding the Sun, the peak wavelength of its radiation matches closely the peak sensitivity of the human eye, probably a causal evolutionary relationship.

Planck's law is probably just mentioned as the formulation that gives the correct, observed shape of the distribution of energy over all wavelengths for a radiating body. The necessity to think of radiation and absorption as occurring in little "squirts" of energy in amount proportional to the frequency of the light wave should be mentioned as leading to the concept of the quantum and eventually to the modern understanding of the behavior of matter on the atomic and nuclear size scale.

35. Only the basic concepts of scattering and absorption need be presented. Spectra will be treated later when needed so the discussion here should be phenomenological rather than in terms of detailed mechanisms. The idea that absorption by a gas gives energy to the gas, heating it, should be gotten across. Also the idea that both absorption and scattering depend generally upon the wave-length of the incident light should be brought out, and the fact that light of shorter wavelengths is more strongly scattered than longer wavelength light (Rayleigh scattering) should be mentioned. This may be cited as the reason why the sky looks blue and why the sunset looks red.

36. There are good pictures of the photosphere available (e.g., in the Hale catalog of slides. Also most texts have good pictures of solar disk showing sunspots and closeups showing granulations). Emphasize that the photosphere is gaseous, not as sharp as it looks, and that the solar atmosphere continues much farther out. Point out that all stars are more or less like the Sun in this respect. The light we see and measure comes mainly from the photosphere of a star, and the things this light tells us about temperature, pressure, turbulence, rotation, composition, etc., really apply only to the photosphere. It is the job of the astrophysicist to

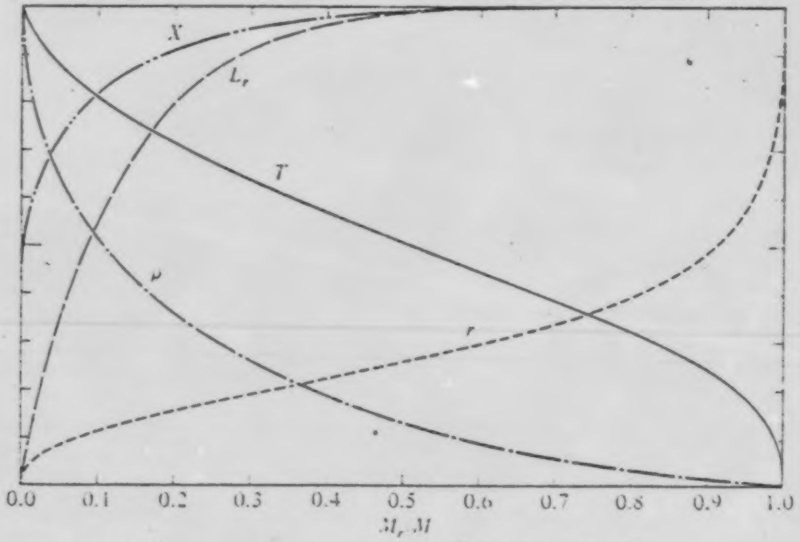
infer from these data about the outer layers of the star what its interior must be like.

37. There is a spectacular motion picture film of solar prominances available for sale or loan - "A Continuous Solar Movie, 6-20 July, 1959" from

World Data Center A,
High Altitude Observatory,
University of Colorado,
Boulder, Colorado 80302

Be sure to emphasize the immense scale of all the solar dynamic phenomena.

38. Interior models of the Sun giving density, temperature, luminosity, and composition as functions of radius can be found in texts on stellar structure and in the literature. See, for example, E. Novotny, "Introduction to Stellar-Atmospheres and Interiors" Oxford Univ. Press, N. Y. (1973). A typical model has characteristics as shown below:



39. The point to make here is that once we know four things, (1) the distance of the Sun, (2) the radiation we receive from it on Earth, (3) the length of time over which it has radiated at approximately its present rate (from fossil data on Earth) and (4) the mass of the Sun, it is evident that a problem exists. The total radiant energy poured out by the sun over the more than 4 billion years of its radiation at the present rate comes to about 2 x 10^{10} joules/gm. This is much more than can be gotten from gravitational contraction or by any chemical process (it is ~0.2 MeV/atom). Only nuclear fission or fusion can give energies of this order and fission is ruled out by the composition of the Sun (mostly H and He with only ~ 2% of heavier atoms) so fusion must be the answer. It may be well to mention the solar neutrino problem here. Despite the fact that we think we know quite a lot about the internal structure of the Sun and especially about its nuclear reactions, nevertheless attempts to detect neutrinos that accompany the fusion reactions give values of neutrino flux less than 1/6 of the value predicted by theory. Something seems to be wrong here somewhere. Point this out to the students and tell them that there is still a mystery to be cleared up. Point out, also, that it has been only recently that the solar neutrino measurements have been precise enough (after nearly a decade of effort on this single research effort) to be able to say that there is a real discrepancy. Up until recently, everything seemed to

be well with our theories of the Sun. Now there comes along a single crucial experiment that doesn't agree with theory; ergo, the theory must be reexamined. Of course, the experiment must also be checked further to make certain the results are reliable. This is a fine example of a living science in action.

40. The step from the Sun to the nearest star is enormous. For example, if you are the Sun, the students the Earth then the nearest star is ~1000 miles away. No longer can any detail of the stars surface be resolved by the most sophisticated telescope - even the stellar diameter can only be measured for a few nearby stars by special methods of interferometry. Thus, all the information we can get about the stars must come to us through its integrated radiation over the whole stellar disk.

Two general types of information can be obtained. Wyatt ["Principles of Astronomy," 2nd Ed., Allyn & Bacon, Boston (1971)] groups these into geometric and intrinsic properties. Geometric properties involve stellar positions, motions, clustering, distances, etc., while intrinsic properties include surface temperatures, luminosities, spectra and chemical composition, mass, radius, and rotation. Not all of these features will be treated in this course; emphasis will be given to the intrinsic properties as being of prime importance from the astrophysics point of view. The geometrical properties are more the province of the astronomer.

41. Two chief ways of measuring stellar distances, one strictly geometric and the other involving several of the intrinsic properties will suffice to show the student what is involved in distance measurement and how it ranges from simple triangulation to indirect methods such as spectroscopic parallax.

The treatments in standard astronomy texts such as Wyatt, Abell, Jastrow and Thompson, Menzel, Whipple, and deVancouleurs, Motz and Duveen, Baker and Frederick, etc., all have detailed treatments of distance measurements. Most go into more detail and treat more methods than are advisable in this course. It is best to stress the concept rather than numbers and formulae. Try to present trigonometric parallax as a simple application of the geometry of "skinny" triangles. Point out the limitations of the method. Angular precision better than 0.01 seonds of arc is rarely achievable so the method is good to distances of less than 100 parsecs (over 300 light years), a volume encompassing roughly 10^6 stars, the local density being about 0.1 star/cubic parsec.

42. The important concept here is that if we somehow know the intrinsic brightness of an object and measure its apparent brightness as it appears in the sky, the inverse square law will give its distance. The trick, of course, is to deduce the intrinsic

brightness of the object from some other observable property than its apparent brightness. For most stars, measurement of color by filter photometry gives a measure of surface temperature which, together with certain other spectroscopic features, allows its intrinsic brightness to be determined because it has been found by studying temperatures and spectral features of stars close enough to measure distance by triangulation that all stars with similar temperatures and of the same spectral class have almost the same intrinsic brightnesses and these brightnesses have been measured for nearby stars for which distances can be measured by parallax. Similarly, the principle has been extended to much larger samples of stars by studying those in a distant cluster such that all stars in the cluster are at nearly the same distance. All of this explanation of course is leading up to the H-R diagram and it may be a good idea to introduce it here in skeletal form with more details reserved for a little later.

It is important to impress upon the student what a great amount of observational work went into establishing the correlation between color or temperature and intrinsic brightness that the H-R diagram summarizes. It should also be emphasized what a marvelous correlation and classification scheme the H-R diagram is. There is probably no parallel in the other sciences except possibly the modern periodic table in chemistry.

43. By "unusual" stars we mean such objects as supernovae whose peak intrinsic brightnesses are well enough known for them to be used as distance indicators when they occur in moderately distant galaxies. The pulsating variables such as the RR Lyrae and Cepheid types also fall into the category of unusual stars. It is not necessary to go into details about the behavior of these distance indicators at this point except to point out that (a) they must be readily recognizable by virtue of some easily observed property (great brightness for supernovae, variability for cepheids, etc.) and (b) they must be "calibrated" - the intrinsic brightnesses of representative samples of the star at known distances must be determined. A lot of astronomy and astrophysics depends upon the accuracy of these calibrations. The classic example of the consequences of an "error" in calibration occured in 1952 when Walter Baade at Polomar found that there are really two classes of cepheid-type variables, and the ones that had long been used as distance indicators were not of the same class that had originally been calibrated by Harlow Shapley but were in fact intrinsically four times as bright so all the distances to galaxies and even the estimated size of the observable universe, all based indirectly on Shapley's cepheid calibration, had to be doubled! A good account of this can be found in Struve and Zebergs ["Astronomy of the 20th Century," Macmillan, N.Y. (1962), pp. 321-330].

There is another interesting and illuminating facet to the cepheid recalibration story. The 200-inch Hale telescope at Palomar was put into operation in 1948, but it was not until early 1952 that Baade used it to observe the Andromeda galaxy, M-31, which just happens to be at the right distance so short period cluster variables (RR Lyrae) of the type Shapley had calibrated cannot be seen in photographs with the 200-inch telescope. However, on the basis of the accepted distance of M31 at that time, these cluster variables should have been visible in the 200" photographs. Baade's first photographs showed instead that longer period, brighter cepheids were visible but not the fainter RR Lyrae variables. Clearly Andromeda was farther away than had been thought. Instead stars known to be four times brighter than the cluster variables were just visible in the photographs. This meant that the distance of M-31 was twice as large as the accepted value determined by Hubble with the 100" observing brighter, longer period cepheids, the only ones he could see in the 100", together with the Shapley calibration. The important point here is that the 200" telescope is probably the only instrument that could have readily discovered this discrepancy. The previous largest instrument, the 100-inch Mt. Wilson telescope, could not see both kinds of cepheids in Andromeda, and there is no other galaxy at just the right distance for the discrepancy to show up clearly between observations with the 100" and 200" telescopes. This shows how closely progress in science is often wedded to the experimental or observational equipment available to the scientist, and it also illustrates the sometimes crucial role of serendipity in science. Baade really didn't suspect anything was amiss. He was a careful, aware observer with the right tools and the experience to recognize at once that something was "wrong" with the pictures of M-31. The consequences of this discovery to the development of astronomy have been enormous.

The development, perhaps one should say the discovery or invention, of radio astronomy by Karl Jansky who was studying noise variations in long distance radio communications links at Bell Telephone Laboratories in 1931 is another good example of the right man having the right instrument in the right place at the right time. The story of Jansky's discovery of the diurnal variation of the radio interference is well known and is at least briefly mentioned in standard astronomy texts. What the texts don't say is that Jansky was using a newly developed vacuum tube amplifier in his receiver, the most sensitive and with the lowest noise level available, and a very large and elaborate antenna system for that time. Without such advanced equipment he would have missed his discovery and without careful observation he would not have found that the radio source of the observed noise was fixed in space near the center of the Milky Way.

The importance of this stepwise advance of science should be stressed, a kind of leapfrog alternating development of instrumentation and discovery. The role of accident in scientific discovery should be carefully conveyed to get across the point that "accidental" discoveries aren't purely accidental but depend upon being observed by a very aware, competent person capable of recognizing them. A prominent physical chemist once showed me a spectrogram he had made in 1930 showing clearly the spectrum of deuterium. He had puzzled over it briefly at the time without realizing what it was before turning to other "more pressing" matters. Two years later Harold Urey announced the discovery of deuterium for which he was awarded a Nobel Prize. There are probably many similar examples of important discoveries overlooked even though the prime ingredients of proper equipment and competent observer were present, but the third essential, the ability to recognize that something of value had been discovered, was missing.

44. In astronomy "luminosity" refers to total radiation from an object. It may be further restricted to a certain wavelength range and still further to the spectral response of a particular radiation detector, in which case it begins to resemble what the physicist usually thinks of in connection with the photometric meaning of the term. These possibilities for confusion can be avoided at this level by sticking to the meaning of luminosity as the total radiation from the stars, $L = 4\pi R^2 \sigma T^4$ ergs/sec. This also has the advantage of simply relating L and T, an idea some pains have already been taken to develop for the student.

45. The treatment of black body radiation has already laid the groundwork for the idea that temperature can be deduced from a star's color. The concept of filter photometry can be introduced here in simple form along lines of two or three-color pyrometry. Spectral classes will be discussed more thoroughly in the following section. It is sufficient at this point merely to say that certain details of a star's spectrum also give clues to its luminosity and temperature in common cases when the star's radius cannot be found, and the $L = 4\pi R^2 \sigma T^4$ relation won't give L from T.

46. This is the usual way to find R. Generally it is only measureable in a few special cases (certain kinds of eclipsing binaries, lunar occultations, and some nearby giants measured interferometrically), and the student should be aware that most stellar-radii are derived quantities, usually from $R = L/4\pi\sigma T^4$.

47. Mass determination is every bit as troublesome as radius, and much more important astrophysically. Its only measurable manifestion is gravitational attraction for other bidies, and practically this means that only relative masses of most binary stars (actual masses for eclipsing binaries) can be determined. Kepler's third law is the key here through observation of the periods of binaries together with their separations which in turn require a distance measurement. Impress upon the students the difficulty and uncertainty

involved in our present observations knowledge of stellar masses. Fortunately for astrophysics, a whole range of stellar models can be developed with mass and composition as the independent variables. The radiative properties of these model stars can be deduced in detail and compared with real stars. Also, in the case of binaries whose masses can be determined a mass-luminosity relation has been found which theoretical stellar models must reproduce. So the lack of observational knowledge of mass for most stars has not blocked development of an understanding of stellar structure and evolution.

48. Only the chemical constituents of the outer layers of the star (its atmosphere) can be directly determined, and this is done by more or less conventional spectroscopic methods. (It is true that for pulsating variables some indirect information about the inner composition can be found by fitting pulsation theory to observation.) The student may be reminded that each element absorbs and radiates light with characteristic wavelengths and the measured wavelengths of these spectral lines serve to identify the elements present in a stellar atmosphere. The problem is in knowing how the surface composition is related to the composition of the interior of the star. Again this is handled in astrophysics in much the same way as the mass: models can be constructed with various assumed interior compositions and the radiative and evolutionary properties of these models deduced for

comparison with the real world of stars. Those that fit are thought to represent the real interior compositions and structures of stars. There is an important uniqueness theorem in astrophysics, the Vogt-Russell theorem,that supports this correspondence between models and real stars if both are in correspondence in surface properties such as luminosity, composition,and in total mass. An extensive and elegant discussion of the V-R theorem appears as Chapter 18 of J. P. Cox and R. T. Giuli ["Principles of Stellar Structure" Vol. 2, Gordon and Breach, N. Y., (1968)]. A more compact and restricted treatment is given by S. Chandrasekhar ["Stellar Structure" Univ. of Chicago (1939), Dover edition (1957) p. 252-3]. The theorem which is provable with few restrictions (see Cox and Giuli) states that the entire structure of a star is uniquely determined by its mass and chemical composition provided that local pressure, opacity, and rate of energy generation anywhere in the star are functions of local values of density, temperature, and composition. This theorem is implicitly the foundation for the whole of astrophysics dealing with stellar structure and evolution.

49. Most astronomy texts give ranges for these quantities. For convenience, they will be listed here as indicated in units of the corresponding quantities for the Sum. Ranges shown do not include some highly abnormal types such as supernovae.

$M/M_\odot \approx 0.04 - 75$; usual range is more like $0.1 - 30$

$L/L_\odot \approx 10^{-6} - 10^{6}$; usual range is $\sim 0.01 - 10^{6}$

$R/R_\odot \approx 0.02 - 100$; usual range is $\sim 0.1 - 10$

$\bar{\rho} \approx 10^{-3} - 100$ gm/cm^3; note: 10^{-3} gm/cm^3 is the density of air at sea level; some super giants have mean densities even lower, as low as 10^{-5} to possibly even 10^{-7} gms/cm^2, a modest vacuum, while white dwarfs have $\bar{\rho} \sim 10^{6} - 10^{7}$ gm/cm^3 and neutron stars reach 10^{15} gm/cm^3. The Sun has $\bar{\rho} \sim 1.4$ gm/cm^3

$T \approx 2000$°C - 100,000°C

Compositions range typically 70-90% hydrogen, 10-30% helium, less than 3% of heavier elements, chiefly things like C, N, O, Ne, Si, Fe.

50. Up till this point little has been said about discrete spectra and atomic energy levels, the treatment being in terms of thermal radiation. This section is meant to introduce the basic concepts of line spectra in a very elementary, qualitative way.

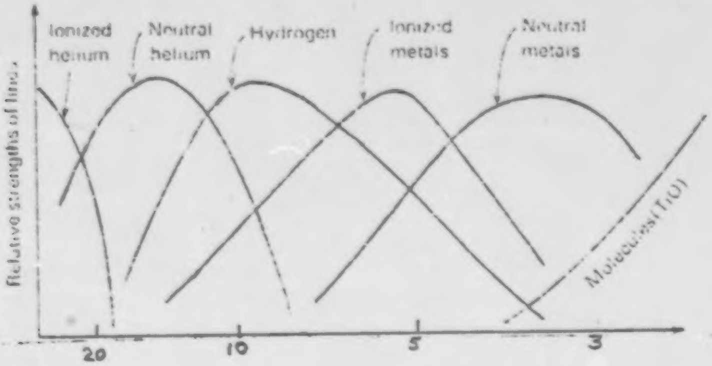
51. Introduce first just the idea that atoms can have discrete energy levels with line absorption and emission resulting from rapid jumps between levels. The qualitative Bohr atom picture may be described here, but it is not necessary and may contribute little if anything to the student's understanding,

except for the concept of an ion (see below). What should be described is the typical energy level (Grotrian) diagram- the simplest sort (H) will do,and no quantitative accuracy is needed, just the idea that the levels are not evenly spaced and crowd together to a limit.

52. The energy level diagram has prepared the way for discussion of excitation and ionization. However, it is necessary to describe the makeup of an atom as electrons bound by electric forces to a positive nucleus in order to talk about ions. If the Bohr atom picture has been introduced, removal of electrons is a natural idea, but the idea of ionization can be presented satisfactorily at this level without reference to the Bohr picture if desired.

53. By spectral sequence is meant here the general appearance of line spectra as one goes from very hot, blue stars (O & B types) down through the sequence to cool, red M-type stars. The concept to get across here is that not only does the thermal radiation identify the star's temperature, but presence or absence of spectral lines and their relative intensities are also indicators of temperature, and in hot and cool stars line spectra may be more sensitive temperature indicators than color. The main features of spectral sequences are given in most standard texts but these are generally too detailed for use in this course. An exception is the treatment in Abell ["Exploration of the Universe" 2nd Ed., Holt, Rinehart, Winston, N. Y. (1969)] whose Fig. 21-1 on p. 408,

reproduced in modified form below; it is just right for purposes of this course. The photograph on p. 103 of Jastrow and Thompson is an excellent supplement to the Abell figure. Abell has a similar photograph of representative spectra, but it is not as clear as Jastrow and Thompson's.



Temperature (thousands of °K)

54. Luminosity class is a difficult concept since it involves the effect of pressure or density upon degree of ionization at a given temperature (i.e., ionization equilibrium via the Saha equation). It is probably best to adopt the chemical equilibrium approach to ionization: $A \rightleftarrows A^+ + e^-$ so higher density tends to shift the equilibrium to the left and vice versa. This approach makes palatable the idea that ionization equilibrium depends upon pressure (density) of the outer atmosphere of a star and that giants with distended, low density atmospheres should show more highly ionized spectra than normal stars of the same temperature. This gives the astronomer a way to sort out various classes of giants, dwarfs, sub-dwarfs, supergiants, etc., all of which may have the same temperatures.

55. Abundance determinations rest on the obvious assumption that the amount of emission or absorption in a star's outer layer depends upon the number of absorbing or emitting atoms present. It follows that if the intrinsic emission or absorption (i.e., the transition probabilities) properties of an atom are known from laboratory measurements, for example, the number of such atoms present in the stellar atmosphere can be deduced. Even simpler (in principle) is measurement of relative concentrations of different atom species by comparison of intensities of their spectral lines.

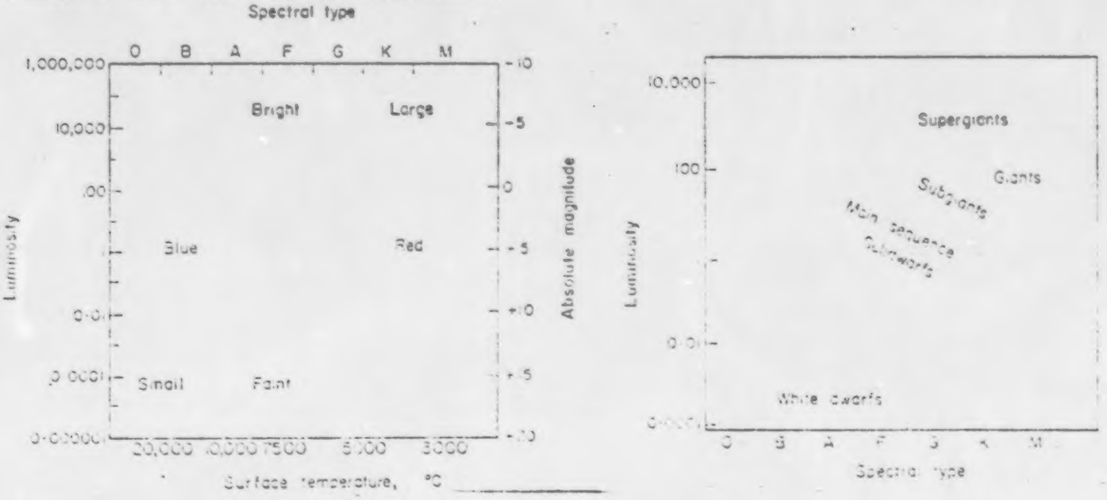
Mention that relative abundances have an important bearing upon both the internal structure and the evolution of a star in a manner to be described later. Current relative abundances (by numbers of atoms) for all matter (stars and interstellar gas) in the vicinity of the Sun is as follows for the most abundant elements:

Atomic Number	Element	Relative Abundance
1	H	3.2×10^4
2	He	2.2×10^3
6	C	11.8
7	N	3.6
8	O	21.0
10	Ne	3.4
11	Na	.06
12	Mg	1.06
13	AC	.85
14	Si	1.00
16	S	.49
18	Ar	.10
20	Ca	.07
24	Cr	.01
26	Fe	.83
28	Ni	.045

All other atom abundances are much lower than the above.

56. All standard texts give full treatments of the H-R diagram; however, not all give a temperature scale and most that do represent temperature in a highly non-linear way. The student may be troubled by a temperature scale increasing to the left. However, it is best not to take too many liberties with the traditional presentation, though temperature should be used instead of such alternates as spectral class or B-V, observationally sensible but astrophysically less directly meaningful than T.

A version of the H-R diagram given by Struve, Lynds, and Pillans, ["Elementary Astronomy" Oxford Press, N.Y. (1959) pp. 262-4] has luminosity and temperature coordinates (in addition to absolute magnitude and spectral class coordinates) and this diagram is reproduced in several more recent texts. A particularly good diagram is given by Goldberg and Dyer [in "Science in Space," Berkner and Odishaw, Eds., McGraw-Hill, N. Y. (1961) p. 346]and this is reproduced in a more recent paperback book by J. C. Brandt,["The Sun and Stars," McGraw-Hill (1966) p. 84]. Another excellent version of the diagram is found in M. Harwit ["Astrophysical Concepts," Wiley, N.Y. 1973) p. 17]. Jastrow and Thompson present a whole chapter, Ch. 5, on the H-R diagram using temperature abscissae and the treatment is excellent for students at this level if some details are omitted. A. J. Meadows ["Stellar Evolution," Pergamon, N. Y. (1967) pp. 13 and 24 (paperback ed.)] gives two rather handy "empty" H-R diagrams, e.g., without any details of distributions of stars but with labels for the main regions:



The Hertzsprung-Russell diagram. (The luminosity is given as a fraction of the Sun's luminosity.)

These "empty" H-R diagrams are good starting places to which details can be added following Goldberg and Dyer. Stress the convenience of the diagram as a means of correlating observational data about a great many stars of all kinds. Also point out that it will be of great utility in describing stellar evolution because positions of stars whose chemical compositions change with time as hydrogen is converted into helium in the interim may be connected with a curve that traces out the observable properties of the star as it grows older. It is this feature that justifies the emphasis put on the H-R diagram in this course.

57. Jastrow and Thompson, pp. 117-118 give a good introduction to the concept of multivariable correlation diagrams by using as an example the distribution of heights among a

human population sample. If this approach is adopted, it is probably a good idea to lead into the H-R diagram by first considering cluster diagrams since the ages of stars in a cluster are all about the same and the diagram as a correlation device is simplified by suppression of age as a variable. Initial chemical composition is also a suppressed variable in cluster diagrams so the correlation becomes chiefly one of luminosity vs. temperature with mass as the independent variable. The other variable, composition, can then be brought in filling up the occupied regions of the diagram.

58. Jastrow and Thompson, Wyatt, Motz and Duveen, ["Essentials of Astronomy," Wadsworth, Calif. (1966) p. 301] give convenient diagrams of nearby stars within about 30 light years. Abell (appendix 12) lists distances, magnitudes, and other features of the 37 nearest stars (within 5 parsecs). Harwit, p. 48, gives a nice discussion of selection effects and the problem of unobserved astronomical objects in general, not just stars. The student should be made aware that observational selection effects can distort any classification or correlation scheme. There may be a great many more very low luminosity stars than we know from observations, and this cutoff effect in observing faint objects occurs at brighter and brighter stars as we look farther away.

59. Emphasize the unfortunate fact that although mass is one of the most important properties of a star for determining its

properties and its life history, it is one of the hardest to obtain observationally. Generally speaking, only masses of binary stars can be measured via Kepler's 3rd law (see Note 47). There aren't very many of these at suitable distances with suitable separations and orientations of the orbital planes to permit precise mass determinations so the sample of stars whose masses are accurately known from direct observations is distressingly small, only about 100 stars, nearly all main sequence types. Less accurate masses are known for perhaps another two or three hundred, again mostly on the main sequence.

60. Both main sequence matching for clusters and the method of spectroscopic parallax for individual stars are covered in standard texts. Emphasize that these widely used techniques owe their usefulness to the H-R diagram.

61. Mention that this is an overall reaction consisting of several chains of intermediate steps and more complicated than this equation. Point out that neutrinos are emitted in some of these steps. Recall the neutrino problem (Note 39). The relative proton and helium masses can be given to show via $E = mc^2$ how much energy is released. Point out that this is the fusion reaction by which we hope eventually to provide man's major energy source but that while the center of a star has its containment problem nicely taken care of by gravity, we must devise an alternative.

The 0.7% efficiency is the energy released upon fusion compared with what would be obtained by total conversion of mass into energy. We don't know any process except matter-antimatter annihilation that can accomplish this, although matter falling into a black hole may radiate as much as ~ 30% of its mass-energy. Even so, 0.7% efficiency is adequate to keep a star like the Sun going for some 10 billion years.

62. Point out that the reason why such high temperatures and pressures are needed for fusion (the Sun's central temperature is about 15 million degrees K and its density is about 160 gms/cm^3) is because of the strong electrical repulsion of a pair of protons when they approach closely enough ($\sim 10^{-13}$cm) to fuse. The high temperature implies high atom velocity needed to overcome this Coulomb barrier. Even so, the reactions have a low probability so high density is needed to produce enough reactions per second to supply the energy radiated from the Sun's surface. Explain also that even at such high densities and pressures ($\sim 10^{11}$atm) matter is in a near ideal gas state because of the high temperature so the astrophysicist deals mostly with matter in the gaseous state.

63. The important concept here is that our familiar and simple Archimedes principle works in stars, too. Show how a small volume of material is buoyed up by the increasing pressure or density as one goes farther into the star and gravity

balances this buoyant force bringing each element of the star into hydrostatic balance.

64. At this point, anticipating a fuller subsequent explanation, one needs only mention that radiation itself exerts some outward pressure as it flows out of the star and in some very hot stars this radiation pressure is large and must be taken into account in the hydrostatic equilibrium of the star.

65. Point out that only a small part of the star near its center has high enough temperature and density to promote fusion so in most stars all the energy is generated in this small central core. It must travel a long way to the surface to escape and in so doing it is scattered, absorbed, and reemitted many times. Emphasize that the fusion reaction doesn't of itself produce heat and "light" but gives off very fast particles and energetic γ-rays that gradually have their energy degraded into heat and light by the many absorptions, reemissions, and scattering events that accompany the journey of the energy to the surface. Note that it takes at least the order of 10^5 years for a gamma emitted in a nuclear reaction at the center of the Sun to find its way out to the surface and be emitted as a visible photon! The solar energy that lights our days began its journey when cavemen roamed the Earth.

66. Explain that radiative transfer involves two steps: absorption of radiation by an atom, raising it to an excited energy

level, and subsequent emission of radiation after a time delay of usually a few billionths of a second. In certain regions of a star where conditions of density and temperature are favorable energy is transported almost entirely by radiative transfer. Point out how a temperature gradient leads to radiative transfer from hotter to cooler regions on the basis of the Stefan-Boltzmann T^4 radiation law.

Explain how radiation pressure must always accompany a net directional flow of radiation using the idea of light as photons or little "squirts" of radiation traveling at speed c but each possessing a small amount of momentum, as a moving billiard ball does, and imparting this miniscule push to an atom upon being absorbed. This is an opportunity to enlarge a little upon the wave-particle dual nature of light, though of course in the context of radiation pressure an explanation can equally well be given in terms of waves alone without invoking the photon.

67. Explain that convection involves mass motion as the familiar example of a pan of water being heated on a hot plate makes evident. Point out that convection takes place when the temperature gradient becomes large enough. Once begun, convection is a more efficient energy transfer mechanism than radiation and this in addition to the mixing effect of convection has important influences upon the internal structure and evolution of stars with convective regions.

68. Point out that the thermal conductivity of a gas is relatively low and under most conditions in stars heat conduction plays an insignificant role compared with radiative and convective energy flow. An exception occurs late in the life of some stars when the H in the center has all been converted to He, and the center is no longer generating enough energy to keep gravity from squeezing it into extremely high densities ($\sim 10^6$gm/cm^3; a teaspoonful would weigh a ton), a condition of matter found in the interiors of white dwarfs, for example. This degenerate matter behaves much like an ordinary metal, the most familiar example of degeneracy, and a degenerate gas, like a metal, is a very good conductor of heat. For this reason, cores of this kind in stars tend to be isothermal and nearly incompressible, both of which properties strongly influence the overall properties of the star.

69. Explain that what we mean by a model stellar interior is really a calculated variation of density, pressure, temperature and composition with radial distance from the center of the star. The calculations are based upon equations derived from the known physics of the nuclear energy generation process, energy transport, and hydrostatic equilibrium. Educated guesses are made as to the central density, temperature and composition, for example, and with these starting values the equations are used to give the run of these variables through the star out to the surface. From these the luminosity, surface temperature, and mass of the star can be determined and

compared with real stars. If there is a real star with the same luminosity, mass, surface temperature, and composition, the Vogt-Russell theorem tells us that our model of that star is unique and corresponds with actual conditions inside the star. The calculations are lengthy and tedious and so are usually done by computer (using a program of several thousand cards!).

70. Main sequence stars appreciably more massive than the Sun ($\gtrsim 2M_{\odot}$), have higher central temperatures and densities sufficient to "burn" H to He by a complex set of nuclear reactions involving carbon, oxygen, and nitrogen nuclei, the CNO cycle. Because this cycle has a very high temperature dependence of its reaction rate (proportional roughly to something like the 14th to 20th power of the temperature) the nuclear energy generating core and its near surroundings have a very high temperature gradient giving rise to a convective, turbulent core outside of which a radiative transfer envelope extends to the surface. This structure plays a fundamental role in the evolution of the star in a manner to be discussed later.

71. Lower main sequence stars ($1M_{\odot}$ and less) on the other hand operate on the proton-proton chain for converting H into He. This has a much lower temperature sensitivity (about T^4) so the temperature gradient in the core is not excessive and does not lead to a convective core. Instead, the core and a considerable part of the surrounding star operate by

radiative energy flow; everything there is well-behaved and quiet with no turbulence or mixing out to about 80-85% of the star's radius where a convective envelope appears extending to the surface. This structure, too, imprints characteristic features on the future life of the star as will be seen.

72. As indicated earlier, we study evolution by means of a series of models connected in a time scale set by such things as the time scale for gravitational contraction, the time it takes to burn an appreciable fraction of a star's hydrogen (~12-14%) into helium, time scales for convective mixing of parts of a star, etc. Such a series of time-connected evolutionary models form a connected track on the H-R diagram and these tracks are the chief means for describing evolution of stars.

73. A little numerical example is instructive here. The Sun radiates about 4×10^{33} ergs/sec., and when about 10% of its mass of 2×10^{33} grams of mostly H has been converted into He, it will begin to evolve away from the main sequence into a red giant. How long will this take? Conversion of 1/10 of its mass means $2 \times 10^{33} \times 0.7\% \times 0.1 = 1.4 \times 10^{30}$ grams will be converted via $E = mc^2$ into energy yielding 1.25×10^{51} ergs. This, radiated at the rate of 4×10^{33} ergs/second will take about 3×10^{17} seconds which is 10^{10} years, the current estimate of the time a $1M_{\odot}$ star will stay on the main sequence. This little calculation may be a bit much for these students,but its essential features can be described

non-numerically and the final result quoted. Everyone is interested in how much longer the Sun will live (it is currently at middle age and has a good 5 billion years to go before it swells up and destroys the Earth, which may or may not be a consolation to the students). This little calculation shows how simply such a piece of information may be obtained, and it also shows how to calculate the life of any other star.

74. Since a star's internal structure is intimately bound up with its chemical composition and especially that in its energy producing core, it follows that as the composition changes by conversion of H into He, the star's structure must readjust itself accordingly. There is no way out for the star which is throwing away its energy into space. It is easy to see, also, that the more prodigally it dispenses its energy, the more rapid must be its structural readjustments and the faster its evolution. Thus, high luminosity stars evolve rapidly, and conversely, stars of low intrinsic brightness take a long time to grow "old". This relation allows us to convert the evolutionary time scale for a main sequence star which was calculated in terms of its luminosity in (73) into a mass related scale, so if we know the mass of a star we can find its lifetime on the main sequence. The M-L relation may be presented as an observationally determined function (see standard astronomy texts) or it may be calculated in an elementary though approximate way from the basic

stellar structure equations, arriving at $L \propto M^3$ [see, for example, Motz and Duveen, p. 379 or Cox and Guili, Vol. 2, pp. 573-576]. The actual main sequence stars obey a relation $L \propto M^n$ with n varying between about 3.5 and 6.5 depending on position on the main sequence. But using $L \propto M^4$ for simplicity, making use of the solar lifetime computed to be $\sim 10^{10}$ years, and including the fact that a star evolves off the main sequence after a fairly definite fraction of its mass ($\sim$12%) has been converted from H to He, one finds a simple relation between lifetime and mass, namely,

$$\tau \approx \left(\frac{M_\odot}{M}\right)^3 \times 10^{10} \text{ years}$$

This shows clearly that massive stars have short lifetimes. For example, a ten solar mass star would stay in the main sequence only about 10^7 years while a 1/2 $M_\odot$ star would live about 80 billion years (much longer than the estimated age of the Universe) before evolving off the main sequence.

75. Most texts show H-R plots for both globular and galactic clusters. The important points to note are that these clusters probably consist of stars that are formed about the same time from material with the same composition. This means that a cluster diagram displays the evolved positions of stars of differing mass but the same initial composition and age. It does not give the evolutionary track of a star moving off the main sequence. The evolutionary tracks as

calculated by Sandage are presented with excellent clarity by Motz and Duveen, pp. 507 and 514.

The age of a cluster can be determined by noting the luminosity at which stars just leave the main sequence. Since L and T together give time spent on the main sequence before evolution toward the red giant stage, the "turn-off" point of a cluster gives its present age. See Fig. 17-9 in Motz and Duveen, p. 303,for an age-calibrated H-R diagram for galactic clusters.

76. Meadows, Chapter 4, gives a good descriptive treatment of star formation including the effects of magnetic fields, rotation, and fragmentation with a sketch of the track of a typical protostar on the H-R diagram. Jastrow and Thompson also give a nice treatment for this course without mention of the angular momentum and magnetic field problems. The pictures in Jastrow and Thompson on p. 169 of the Herbig-Haro No. 2 object in Orion showing a new star forming is a very poor reproduction and wouldn't convince anyone. A much better reproduction of this is to be found in S. J. Inglis ["Planets, Stars, and Galaxies," 2nd ed., Wiley, N. Y. (1967)], p. 316.

77. The observable protostars: Herbig-Haro objects, T. Tauri variables, and the recently observed infrared emission nebulae are all located in regions of relatively high gas and dust content. This makes sense if stars are to form from gravitational condensation of interstellar gas and dust.

Jastrow and Thompson, pp. 163-172, give a nice discussion of the progress of such a condensation.

78. Explain how gravitational contraction heats a gas through collisions between the rapidly infalling atoms and slower atoms farther in that have been slowed by earlier collisions. This conversion of inwardly directed motion imparted by gravity into random (heat) motion through collisions is the key to heating by gravitational contraction.

79. The time scale for gravitational contraction, the "Kelvin" time, is the time required to radiate away the fraction of a star's gravitational potential energy that can be converted into heat (as allowed by the virial theorem. See Cox and Giuli, Vol. 1, pp. 4-5, for a brief treatment). The result, again using $L \propto M^4$, is that the Kelvin time is order of 10^7 $M_\odot/M$ years. The only point that needs to be made to the students is that this contraction time and the accompanying loss of heat by radiation is a "fast" process taking roughly 10 million years.

80. See Meadows or Jastrow and Thompson for typical pre-main sequence evolutionary tracks. For more detail, Novotny, pp. 278-297, is a good source. The right hand part of the protostar track up to the luminosity maximum is straightforward, but the students may wonder why the subsequent track bends down almost vertically. This is caused by extensive convection in the star causing much of it to become nearly isothermal while continuing to contract; its luminosity

decreases because its radius decreases while its temperature stays nearly constant. This condition is maintained generally until the core becomes hot enough for nuclear reactions to begin. These generate enough energy to stop further contraction and to raise both T and L so the track turns left and moves to higher T and somewhat greater L until the star adjusts itself to the new conditions of nuclear energy generation and settles down to begin life on the main sequence.

81. Hydrogen burning begins to be significant at core temperatures of a few million degrees. This occurs about 10^7 years after the beginning of contraction for a star of one solar mass. It then takes about 4×10^7 more years before a 1 $M_\odot$ star reaches the "zero-age" main sequence. All of this takes only a very small fraction (0.5%) of the total lifetime of such a star.

82. Explain that convention says a star is born just when it reaches the main sequence, and its age is reckoned from that time.

83. Sandage and Gratton [in Proc. Int. School of Physics, Enrico Fermi, Course XXVIII, "Stellar Evolution", Academic Press, N.Y., 1963, pp. 11-22] give a nice discussion based on homology transformation theory showing how a star evolves upward along the main sequence as it converts H to He. See also Cox and Giuli, Vol. 2, Ch. 22. Iben and others (see Novotny, pp. 319-324) have shown that heavier stars move along tracks characterized by increasing R and L but slightly

decreasing T while in the main sequence band. For the student it is sufficient to say that as a star's composition changes by depletion of its hydrogen, its central temperature and density must increase to keep up the energy generation rate as the "ashes" of the hydrogen burning process, namely He and some heavier elements, gradually accumulate. This hotter core raises both the surface temperature and luminosity in such a way that the star moves upward and either to the left or right on the H-R diagram depending upon its mass but always within a narrow band defining the main sequence until about 10% of its total hydrogen has been consumed at which point its track moves upward and to the right away from the main sequence on its way to becoming a red giant.

84. The nuclear burning time scale has already been defined in (74). A point to be made here is that it is because a star spends most of its lifetime ($\sim 90\%$) on the main sequence that most of the stars we can observe are of the main sequence variety. Those stages of evolution which are rapidly transversed, such as the protostar gravitational contraction stage ($\sim 10^7$ yrs.), don't have many stars in them at any given time, and we can observe relatively few such stars. The long, slow stages of evolution are, on the other hand, well populated at any given time and many such stars can be observed. This fact gives some rough clues from observation about the relative time scales of various evolutionary stages.

85. Stars more massive than $\sim 2M_{\odot}$ have high enough central temperatures and densities to operate largely on the CNO nuclear energy cycle with its very high temperature sensitivity ($\sim T^{16}$) giving a convective core with radiative envelope. These are categorized as upper main sequence stars. Less massive stars run on the p-p chain with more like a T^4 sensitivity, and these stars have radiative non-turbulent cores with convective envelopes. These lower main sequence stars evolve differently from the UMS stars. The differences are already evident from the two different types of tracks followed on the main sequence. The LMS stars follow tracks that move upwards and to the left for a time from the zero-age point while UMS stars move initially to the right and slightly upward from zero-age and make a couple of reversals of direction before leaving the MS.

86. Again Meadows gives a nice description with reasonable details about the red giant phase of evolution while such books as Cox and Giuli, and Novotny give more thorough reviews of the modern literature, and the standard astronomy texts treat post-MS evolution only briefly and often superficially. Since the detailed theory of these stages of evolution has only been worked out in the last decade, and since for some of the later rapid stages near the helium flash and beyond the theory has only just recently been developed and is still a contemporary research field, there is good reason why the elementary texts, particularly the older ones, do

not have much to say about the subject. For students at this level the treatment in Jastrow and Thompson seems about right,and Meadows gives more detail if desired.

87. Point out that once the core exhausts its hydrogen fuel,it is no longer able to withstand the pressure of the overlying stellar matter, so it contracts gravitationally and heats up more, eventually to temperatures sufficient to cause He to "burn" by the process $3He \rightarrow C$, the triple-alpha process. This requires about 10^8 degree temperatures. Point out that it is gravity alone that causes this large temperature rise from about 20 to 100 million degrees in the same way it supplied the protostar's energy before nuclear reactions began. gravity thus always stands ready to take over energy production whenever other means fail in the star.

88. As the helium core is further heated by contraction, its outer fringes keep a thin surrounding shell of gas which still contains some hydrogen hot enough to maintain hydrogen burning in the shell. As time goes by, the shell must move outwards to find new hydrogen fuel in much the same way that a grass fire burns outward from its central starting point. As this hot H-burning shell (~20 million degrees) moves onward,it heats the overlying material causing it to expand so the star becomes both larger and more luminous. Since $L \propto R^2 T^4$, it doesn't require as high a surface temperature anymore to radiate all the energy being produced; consequently it's surface grows cooler and redder. It has developed all the characteristics of a red giant: large size, high luminosity,

cooler and redder surface, extended low density atmosphere.

89. Point out the sharp "spike" at the red giant luminosity peak and describe this "helium flash" as due to a sudden burst of energy in the star when the triple-alpha process begins burning He to form carbon. The suddenness of the flash which appears only in LMS stars between $\sim .5$ and 1.3 $M_\odot$ is due to the fact that the He core is initially degenerate and therefore nearly isothermal. The onset of He burning converts it back into an ordinary gas which expands explosively causing the star's envelope to expand, suddenly increasing the luminosity on a time scale of only hours. Nuclear energy is generated in the core for a short time at a rate ~ 100 times the luminosity of the whole Galaxy, but most of this is absorbed by the expanding core so the star itself increases in luminosity only by a factor $\sim 10^4$ times the Sun's luminosity.

Stars $\lesssim 0.6M_\odot$ never generate enough heat by contraction of the core to make it nondegenerate and these don't exhibit a He-flash. Instead they evolve toward the white dwarf region without undergoing a red giant stage.

More massive stars than approximately $4M_\odot$ never develop degenerate cores and the 3α He burning can begin without core popping and helium flash. In between 1.3 and $4M_\odot$ the cores are only partially degenerate, and the He flash is greatly reduced in intensity.

90. Books on stellar structure and evolution give post-MS tracks to the red giant stage. See Cox and Giuli and Novotny. Most sources quote Iben in "Annual Review of Astronomy and Astrophysics" Vol. 5, [Ann. Rev., Palo Alto, Calif. (1967), p. 571], which is authoritative, to say the least, and which contains some excellent late evolutionary tracks for a wide range of stellar masses. Once again, these references are mainly for the enlightenment of the instructor, not for teaching models at the level of this course. For this, Jastrow and Thompson provides a good guide with excellent HR diagrams and pictures of the various model stars in cross section.

91. The triple alpha process has been described as the principal nuclear energy source following exhaustion of H in the core. As the He burning proceeds, the core becomes depleted in He and rich in C^{12} which is inert at He burning temperatures. Eventually, in sufficiently massive stars ($\gtrsim 8M_\odot$) the C^{12} core may be sufficiently heated by gravitational contraction for carbon to begin capturing He, $(C^{12} + He^4 \rightarrow 0^{16})$, which requires an ignition temperature of about 6×10^8 degrees. This may lead to a carbon flash if the He core is initially degenerate.

92. As Iben's models show, the heavy stars make post-MS tracks that move more and more horizontally into the red giant region as more massive stars are considered, and above $\sim 4M_\odot$ there is no He flash.

93. Below $\sim .5M_{\odot}$ the triple alpha reaction is not ignited and once H burning ceases the star with a degenerate, nearly isothermal core which is relatively incompressible moves far below the main sequence and cools slowly rather like a ball of metal would until it is too faint to observe, a "black dwarf".

94. Evolution following the red giant stage is characterized by a number of short time scale processes [see Iben, Cox and Guili, Novotny] that move the star back and forth horizontally on the HR diagram. During some of these stages, the slower ones, the star exhibits secular instabilities and becomes one of several types of variables, e.g., cepheid, RR Lyrae, W Virginis, etc., depending upon mass, composition, and stage of evolution. There is also a region in the HR diagram in which very few stars are found, evidently a region rapidly traversed in post-giant evolution--the Hertzsprung gap.

95. Novae represent a special case in that they appear to be a late evolutionary stage of close binary stars, close enough for appreciable mass transfer to take place from the one that first starts to become a giant to its smaller partner. The transfer of mass then acts to speed evolution of the less massive star while retarding the development of the one that originally evolved first. This seesaw pattern of evolution in the early post-main sequence period is an example of how the pair of stars influence each other. The mechanism for the explosive flare up of a nova is still not understood and various modern theories attribute this to (a) nonradial

oscillations of one star resonating with the period of revolution of the companion, (b) mass accretion by one member of the pair (which must be a white dwarf in this theory) leading to rapid, probably explosive burning of the transferred mass when enough has accumulated, or (c) development of a degenerate, non-burning $He^4 + C^{12}$ shell in the first star of the pair to evolve toward the red giant state, this shell being eventually compressed enough by gravitational contraction to start He burning which shortly raises the shell temperature enough to remove its degeneracy. This creates a shock wave and a quick increase in luminosity very much as in the helium flash in red giants.

Probably the main point about novae to try to get across is that as a result of the interaction between the two stars in a close binary, neither evolves in the same manner as a single star. The nova stage is an example of this difference in evolution, but its details are yet to be worked out fully.

96. Chandrasekhar showed that a degenerate core can stand its own gravitational pressure only if it is less massive than 1.4 $M_\odot$ so for less massive stars contraction, following He burning (or even H burning in very low mass stars), is stopped by the relative incompressibility of the degenerate core electrons. This halt stops further gravitational core heating, and when the H burning shell has finally reached the surface, consuming the last bit of nuclear fuel, the star will have collapsed onto its degenerate core so it consists simply

of a small ball of high density degenerate matter with a thin, nondegenerate skin. Its small radius means low luminosity, so it ends up far below the main sequence; it is still quite hot $\gtrsim$ 10,000° so it is white in color and its low luminosity and high heat capacity mean that it will cool very slowly (the time scale is order of 10^9 years for the luminosity to drop by half), eventually becoming redder and fainter so it moves downward and to the right of the HR diagram toward the dwarf region in times greater than the age of the Universe.

97. The white dwarfs must be less massive than 1.4 $M_\odot$, the Chandrasekhar limit. Measurements on WD's that are members of binary systems confirm the low mass prediction. The question whether stars initially more massive than $\sim$1.4 $M_\odot$ state is not firmly settled, but the existence of a WD in the Pleides cluster with a turn-off from the Main Sequence at $\sim$ 6 $M_\odot$ strongly suggests that this WD originally may have been as massive as 6 $M_\odot$.

98. Describe planetary nebulae (see standard texts) and note that they are located far to the left on the HR diagram at roughly the luminosity level of the horizontal region occupied by cepheids and RR Lyrae variables. In this respect they seem to be part of a looping track that joins these variables with the white dwarfs. These variables are known to eject matter into space as the planetary nebulae do. Moreover, the central stars of many planetaries already begin to resemble white dwarfs. They are now generally thought to be the link between late red giant evolution and the final WD stage.

The shell of a planetary rarely contains more than $\sim 0.2\ M_{\odot}$, but until it expands enough to become transparent, it hides the hot core of its parent red giant, so at the onset of transparency the star would appear to move rapidly from red giant to planetary nebula regions of the HR diagrams.

99. If the core mass of a red giant exceeds $\sim 1.4\ M_{\odot}$, the degenerate core is not strong enough to withstand gravity, and the collapse does not stop but continues, heating the core to the C-burning ignition temperature and beyond. At $\sim 10^9$ degrees a whole range of nuclear reactions are possible leading to more or less rapid buildup of heavy elements up to the region of iron and nickel which are the most stable nuclei. Each of these heavier elements has higher binding energy per nucleon so it generates less energy until near Fe and Ni a maximum in the binding energy/nucleon is reached and further thermonuclear buildup ceases.

100. It is necessary at this point, if it has not been done earlier in connection with the solar neutrino problem, to explain to the student what a neutrino is, that it moves with the speed of light and carries away energy, that it does not interact much with matter and can on the average go through an entire galaxy without a collision or more to the point, it can escape from the center of a star with only an insignificant chance of being stopped. (Its mean free path is ~ 2 light years in lead!) Also explain that in all

the nuclear "burning" processes that go on in stars neutrinos are given off and carry away a small amount (~1%) of the energy in H and He burning. But above 10^9 degrees when all sorts of additional reactions take place leading to heavy element buildup, the neutrino output increases rapidly until it begins to carry away a significant amount of energy from the star's interior. The star tries to adjust for this cooling effect on its core by contracting to heat it up again to preserve the energy generation rate. But this is a losing game, for raising the temperature just boosts the neutrino production and further "refrigerates" the core, leading to a vicious circle and shortly to a catastrophic collapse. As the central temperature rises to several billion degrees because of contraction brought about by neutrino loss, a point comes at $\sim 8 \times 10^9$ degrees when the iron nuclei breakdown according to the reaction $Fe^{56} \rightarrow 13He^4 + 4n - E$, $13He^4 \rightarrow 26p + 26n$. This is a very endothermic reaction since E is comparable to the entire energy output of the reactions that build up the Fe^{56} from He in the first place, and once it starts,it regrigerates the core almost instantly and catastrophic collapse of the core follows at once, the time scale being the free fall time, of the order of $(\bar{\rho}_c)^{-1/2}$ hrs. which for typical core densities at this stage is only of the order of a few tens of seconds.

101. Gravitational collapse of the core releases quite a lot of energy (~the gravitational potential energy of the core which is large because the core is massive). The neutrino

energy loss rate just preceeding Fe^{56} dissociation at $T \sim 5-8 \times 10^9$ degrees may exceed the luminosity of an entire large galaxy like the Milky Way by a factor of 1000 ($\sim 10^{47}$ ergs/sec $\approx 10^{14} L_\odot$).

102. Even though a normal star is virtually transparent to a neutrino, such enormous neutrino fluxes as this do produce enough collisions with the abnormally high density region just outside the core at this stage of the supernova to eject considerable matter. Mass ejection is further aided by the shock waves that emanate from the core when its collapse is eventually halted by baryon degeneracy, i.e., when its density becomes so large ($\gtrsim 10^{11}$ gms/cm^3) that a neutron star can form by $e^- + p^+ \rightarrow n$. Whereas electron degeneracy provided the rigidity needed to halt gravitational collapse at the white dwarf stage if the mass was not too large, here it is degeneracy of the nucleons that stops the collapse at the neutron star stage. The shock wave is presumably initiated when the relatively rigid neutron star forms suddenly in the collapsing core and further infalling material rebounds quickly from its initial radial compression upon striking the neutron core.

103. Heavy neutron and gamma production just preceeding and during the iron dissociation provides an essential building block for nuclear reactions that lead to production of neutron rich isotopes of the elements heavier than iron. It is worth remarking that every atom of gold or silver in student's rings or dental fillings was born in the heart of a supernova

explosion more than 5 billion years ago, before the solar system came into being.

104. If the above picture of the formation of a supernova is correct [See, however, Schramm and Arnett, Phys. Rev. Letters 34, 113 (1975) for a somewhat altered scenario], much of the envelope of the massive star should be ejected into space by the shock waves and neutrino blast wave, leaving behind a neutron star residue. Theory suggests that the neutron star must not be too heavy itself, or it will collapse to form a black hole, so all but about one solar mass of the original star of perhaps several or even several tens of solar masses must be ejected in the explosion and returned to space enriched in heavier elements to serve as raw material for the formation of a later generation of stars, (unless, of course, black hole formation is a common end for heavy stars). Each succeeding generation of stars ought then to have a higher heavy element concentration.

105. A neutron star, being a sphere of degenerate matter, ought to bear more than a passing resemblance to a white dwarf in structure. At normal nuclear densities ($\sim 10^{15}$ gms/cm^3) a neutron star of 1 $M_\odot$ would have a radius of only about 10 km, ~6 miles, and a pinhead sized piece of it would weigh 10,000 tons. Harwit, Fig. 8.16, p. 365, compares the structure of a white dwarf with the best current estimates of the detailed structure of a neutron star in which much of the degenerate nuclear matter is thought to be in the form of a superfluid.

There may be a very strong magnetic field associated with a neutron star (order of 10^{12} gauss if flux is conserved in the collapse), and it should rotate very rapidly, as fast as ~ 30 revolutions per second as a result of conservation of angular momentum in the collapse, assuming the initial red giant rotated at the normal rate for the stars believed to form supernovae that lead to neutron stars.

106. Standard astronomy texts give light curves, peak luminosities, spectral features, and other properties of supernovae. The peak luminosities are sufficiently well established for supernovae to be useful distance indicators in distant galaxies because their great brightness, comparable to or sometimes exceeding that of the whole galaxy, makes them stand out when they occur. The frequency of occurrence is not known very accurately but is generally estimated to be in the range of one every 30-300 years in a galaxy like the Milky Way, and these frequencies are consistent with the hypothesis that all massive stars $\gtrsim 6\ M_\odot$ become supernovas.

107. The Crab Nebula is the best resolved, most thoroughly studied supernova remnant. Its supernova explosion is accurately dated at 1054 A.D. Its radiation has been very well studied and characterized. Its mass ejection rate is accurately known. It has a pulsar at its center and this is believed to be the neutron star remaining after the SN explosion. The observational material is summarized in most astronomy texts and several have excellent pictures of the Crab in color. Since it is close enough and recent enough to be

observable in great detail and since it exhibits so many important features of high energy astrophysics, it is one of the most important objects in the sky to the astrophysicist.

108. The important concept here is that an accelerated charged particle radiates electromagnetic energy, so a fast particle such as an electron travelling in a curved path must radiate. Explain also that a charged particle in a magnetic field moves in a curved path - if the field is uniform the charge particle moves in a helical path about the magnetic field. Point out that synchrotron radiation is the result of fast electrons circling about magnetic lines of force and is observable in the lab and on a cosmic scale as well. It has characteristic features of its spectra and polarization (explain polarization briefly and phenomenologically in terms of light through polaroids) that make it recognizable in starlight. Make the point that when synchrotron radiation is detected, we know its source contains very high energy (relativistic) electrons and magnetic fields. The intensity of the radiation also permits estimates of the density of the electrons to be made. This has been done in detail for the Crab, and the total energy radiated away in light and other electromagnetic radiation since 1054 A.D. plus the kinetic energy of the expanding gas cloud (obtained from velocity measured by Doppler shift) plus the energy in

the expanded magnetic field, all taken together give an estimate of the total energy expended in the original Crab supernova explosion.

Finally, the synchrotron process is important for generation of radio waves. Strong radio sources are always found to be synchrotron sources.

109. In general the visible mass ejected in a supernova explosion is of the order of a solar mass (from a sizeable fraction to well over one $M_{\odot}$) and ejection velocities range up to 0.1c. The total mass ejected may amount to several solar masses. Doppler measurements of the ejection velocity together with the size of the region of ejected matter give the time since the explosion.

110. The more recent introductory astronomy texts such as Wyatt (1969), Jastrow and Thompson (1973), Menzel, Whipple, and deVaucouleurs (1970) give brief descriptions of the chief properties of pulsars. These are probably adequate for this course. All of the observed features such as precise pulse repetition rate, gradual slowing down, presence of very short time scale components in the pulse ($\sim$100 μsec) implying a very small source, total energy associated with the source, etc., all point to a rapidly rotating neutron star emitting radiation in a more or less sharply defined beam that rotates with the star. The detailed mechanism of the radiation source is still not settled, but it does have synchrotron characteristics implying relativistic

particles (probably electrons) and magnetic fields. The article by A. Hewish in "Annual Review of Astronomy and Astrophysics" Vol. 8, Annual Reviews, Inc., Palo Alto, Calif., 1970, gives a good review of both observational and theoretical aspects of pulsars, the latter in rather abbreviated form, however. See also Ruderman's more recent review in Vol. 10 (1972) of Ann. Rev. of Astron, Astrophys. which gives more discussion of theory.

111. This aspect of supernovae has been briefly mentioned earlier. Since the mass ejection is the order of several $M_\odot$ and the SN frequency roughly one/century per galaxy of, say 10^{11} stars, there ought to have been several times 10^8 $M_\odot$ ejected into our Galaxy by supernovae during its lifetime $\sim 10^{10}$ yrs., representing a return to the interstellar medium of nearly 1% of all matter originally bound up in stars. This material is enriched in heavier elements (heavier than He) but still does not represent much enrichment in terms of the mass of the Galaxy. But supernovae occur mostly in regions such as the galactic disk where the local density of interstellar matter is considerably higher than average because this is where the exploding star was originally formed, so supernova enrichment of this material is proportionately greater, and it is not hard to see that 10^8 supernovae could enrich the regions of star formation in a galaxy to levels of a few percent of heavy elements, as found in the Sun, for example.

112. This is a very old concept in general relativity dating back to K. Schwarzschild's spherically symmetric solution to Einstein's equations of general relativity in 1916, but it has lain dormant until the last decade or so when interest in neutron stars (also old, dating back to the late 30's) revived. The question of the black hole comes up when one asks what happens if a neutron star is too massive for degenerate neutron matter to support the gravitational pressure. It will collapse further, but into what form? The Schwarzschild solution leads to a singularity at a distance $R_s = 2GM/c^2$ for a mass, M, and there are no geodesics connecting the outside world with events inside R_s hence no light signals can communicate to the outside world any information from within R_s. The best way to present the properties of the black hole to students at this level seems to be in terms of the action of gravity upon light. This can be done non-relativistically in a very simple way for students with some elementary physics background: The total energy of a particle with mass, M, and velocity, v, at a distance r from a heavy body of mass, M, is just $E = 1/2\ mv^2 - \frac{GMm}{r}$. If $E > 0$ the trajectory is hyperbolic, and the particle flies off to infinity with excess kinetic energy; if $E < 0$ the trajectory is an ellipse; if $E = 0$, the particle is just able to escape. Thus, the escape velocity $v_e = \sqrt{2GM/r}$. Now let the "particle" be a photon with $v = c$ and ask what must r be in order that c be the escape velocity, v_e. The answer is $r = R_s = \frac{2GM}{c^2}$, the Schwarzschild radius. So R_s

defines a sphere about M such that a photon starting out from within R_s cannot escape but will circle back under the influence of the strong gravitational field of M. It is forever a captive of M. Thus, no messages about conditions within R_s can ever get away to be received in the world at large.

A completely non-mathematical description of a black hole can be given in terms of the local distortion of space-time using the rubber membrane analog for the 4-dimensional space-time warp caused by a gravitating body. A very lucid treatment of this with extensions to cosmology is given by W. J. Kaufmann, "Relativity and Cosmology", Harper and Row, Evanston, (1973)(paperback).

An alternative approach, if time does not permit more than a brief treatment of the black hole, is to say that strong gravitational effects can only be treated accurately by the theory of general relativity. One of the tested predictions of this theory is that light is bent in a strong gravitational field and if a body is massive enough and also small enough, light from its surface is prevented by the strong gravitational attraction from escaping. Such a body would appear as a black hole because no light could escape from it and any light hitting it would be absorbed forever. Such an object can't be "seen" by light or any other electromagnetic radiation, and no other kinds of particles, electrons, neutrinos, or anything else can ever escape from within it.

It does betray its presence by its gravitational field, however, and can be detected by its gravitational pull on other bodies. For example, there is mounting evidence that the x-ray source in Cygnus (Cyg X-1) may be a close binary star, one member of which is a black hole, the x-ray emission coming from the acceleration of ionized matter being drawn into the black hole from its visible neighboring star.

113. Standard astronomy texts all treat the Galaxy in adequate detail. There are three excellent pictures worth showing the students: the Lund Observatory panoramic picture of the whole Milky Way as seen from Earth covering the whole 360° sky, the Oort, Kerr, Westerhout drawings of the spiral structure of hydrogen, and the great star cloud in Sagittarius. The first two are widely reproduced in most texts. The latter is reproduced in Motz and Duveen p. 516 and is available as a slide from the Hale catalog. (Cat. No. 155)

114. Since we are within a dusty, gassy spiral arm, our optical view of the spiral structure is limited by dust obscuration to adjacent arms and only the near parts of those. Our view of the nucleus is severely limited. Radio waves are not absorbed by dust, so much of our knowledge of the spiral structure is from radio astronomy. Obscuration by dust and gas for the optical region of the spectrum is very large, a factor $\sim 10^8$ between us and the center of the Galaxy. However, explain that radio astronomy mainly gives information about

the distribution of neutral atomic hydrogen from the 21-cm. absorption line and tells little about the distribution of stars which are very weak radio emitters except for such cataclysmic types as supernovae. A strong correlation between star population and hydrogen gas density has been demonstrated for nearby arms (where both can be observed, the stars by optical telescopes and the H by radio telescopes) and by observations of nearby spiral galaxies like M31 and M81 that are close enough to resolve stars and spiral arms in 21-cm radio emission. This correlation supports the assumption that the radio arms in our Galaxy also define the star-populated arms as well.

115. Main sequence H-R diagram fitting has already been mentioned as a means of measuring distances to clusters. The practical application is in defining the distributions of globular and galactic clusters in the Galaxy. Likewise, the short period variables (cepheids and RR Lyrae) have been mentioned as being easily recognizable and having intrinsic brightness related to their period, so they too serve as distance indicators for single stars.

116. These slides are chosen to show two things: The dusty regions of the galactic disk and regions of star formation in the dusty areas. See Appendix A for notes on each slide.

117. The subject is well covered in standard astronomy texts. The concept to get across is that Doppler measurements give

relative motions between Sun and observable stars in both disk and halo. If the individual small variations in velocity are ignored, there emerges an overall picture of the orbital motions of the stars about the center of the Galaxy. This motion is nearly simple Keplerian orbital motion well outside the nucleus where we are, and careful observations of the Sun's orbital motion show the period to be about 200 million years. Knowing the distance from the nucleus, Kepler's 3rd law gives the total mass of the Galaxy inside the Sun's orbit. Adding the estimated small fraction outside the solar orbit gives the total mass $\sim 10^{11} M_{\odot}$. This illustrates again the power of simple physical laws ingeniously applied: how else could one conceive of measuring the mass of an entire galaxy? Point out also that this method works equally well for nearby resolvable galaxies such as M31; in fact, it is easier to do for an external galaxy. Details of the actual rotation velocity vs. distance from the nucleus showing quasi-rigid body rotation in the nucleus, gradually changing to Keplerian motion at large distances may be given if desired but may well be omitted in this course.

118. Most texts point out the similarity of the Galaxy to M31, the Great Spiral Nebula in Andromeda, and give excellent pictures of M31, generally printing the Hale catalog slide, Cat. No. 150, and S-24, M81 is also believed to be similar to the Milky Way.

119. The widely reproduced neutral hydrogen distribution map of Oort, Kerr, Westerhout, to be found in most texts and in Shklovsky,["Cosmic Radio Waves," Harvard University Press, Cambridge, Mass. (1960)]. Motz and Duveen and Jastrow and Thompson have good reproductions. Struve and Zebergs (p. 433) shows a superposition of HI regions upon nearby clusters and cepheids delineating the spiral arms in the region of the Sun.

120. Standard texts all treat this subject in more than adequate detail. The key idea to get across is that the distribution of Pop. II stars in the halo and nucleus taken together with their great age ($\sim 10^{10}$ yrs.), their pristine composition (little or no elements heavier than He), and the fact that they are found in galaxies of all types (spirals, barred spirals, eliptical, irregular) leads to the important and relatively new conclusion that galaxies probably do not evolve from one type to another but were instead all formed at about the same time with some other property than age (probably angular momentum) determining their present differences in form. This follows from observations that Pop. II stars of approximately equally great ages are to be found in all types of galaxies, implying that all are at least as old as these stars ($\sim 10^{10}$ yrs.). That some of these galaxies are still making stars at a slow rate may be explained as a result of the slower accumulation of gaseous, dusty regions of sufficient density to initiate star formation.

121. Interest in the nuclei of galaxies has developed so recently that the subject is not treated in even the most up-to-date introductory texts. The best reference on the subject is a collection of papers given at a Vatican Study Week and published under the title "Nuclei of Galaxies" Ed. by D. J. K. O'Connell,[American Elsevier Publ. Co., N. Y., 1971.] Study of galactic nuclei is a promising frontier in modern astronomy and astrophysics and may well hold the answers to several questions of major importance. the nature of QSO's, the origin of enormous infrared energies emitted by some galaxies, the mechanism of mass ejection from active nuclei, explosions of galaxies like M82, the origin of strong radio galaxies, and the evolution of galaxies. Since the galactic nucleus seems to hold the key to such vital questions, the subject deserves at least a brief review.

Most galaxies, even many of the irregulars, have a small central region with diameters ranging between a few light years and a few hundred light years in which the density of stars increases rapidly toward the center, reaching values as large as $10^8 M_\odot$ per cubic parsec (1 parsec, pc, = 3.26 light years). In our own Galaxy within a radius of 20 pc., Oort has estimated a total mass of $1.6 \times 10^8 M_\odot$ or roughly 0.1% of the whole mass of the Galaxy with an average stellar density $>10^6$ times that in our own neighborhood. Star types found in the nuclei of galaxies are old Pop. II types including many low luminosity red dwarfs that have very long lifetimes on the main sequence ($\sim10^{12}$ years, much longer than the present life of the galaxy, hence these stars have evolved little since reaching the Main Sequence). This is an important point since it implies that all nuclei containing such old stars are themselves old and supports the idea that all galaxies were formed at about the same epoch in the evolution of the Universe rather than some types of galaxies having evolved from others.

The average star densities, even within $\sim$1 ly of the center of a typical nucleus ($\bar{\rho}\sim10^6 M_\odot pc^{-3}$) is still too small for stellar collisions to be frequent. A rough calculation gives about 3×10^{-7} collisions per year per cubic parsec, and even if each collision resulted in a supernova or comparable energy releasing process, the energy thus released would not account for the observed energy emitted. The collision rate goes as the square of the star density, however, and if the density increases steeply toward the center, as some recent observations suggest, to values of the order of $10^8 M_\odot/pc^3$ within .01 pc or less of the center, then collision rates become significant for energy production and might be able to account for the strong radio and infrared emission observed from some compact nuclei.

It has been suggested that both the observed energy and normal mass ejection rates by nuclei might be accounted for by matter falling into black holes formed inside dense nuclei.

If a black hole is formed with some angular momentum, matter entering it can radiate its binding energy just before disappearing down the hole [Lynden-Bell in "Nuclei of Galaxies" pp. 527-537 and Nature, 223, 690 (1969)]. This radiation and the mass it ejects by radiation pressure could, according to this hypothesis, account for the activity of nuclei. Wheeler ["Nuclei of Galaxies", pp. 539-567] has proposed a black hole mechanism for ejection of jets of matter as observed in a number of active nuclei (e.g., the quasar 3C 273, the galaxy M-87 etc.), and several people have proposed ways in which black holes could form within nuclei. These ideas are all somewhat speculative but all are supported by reasonable analysis and lead in plausible ways to rates of energy and mass ejection that compare reasonably well with observations.

The observations appear sufficient at the present time to lead to the following generalizations:

1. Most galactic nuclei are active to some degree
2. Matter (gas, relativistic particles, and perhaps sizable objects) is ejected from active nuclei
3. Very high star densities exist in the central nuclear regions of at least our Galaxy and M31
4. Infrared power levels of 10^{41} to > 10^{46} ergs/sec have been observed from active galactic nuclei, orders of magnitude greater than the optical and radio emission from such nuclei. These figures don't include quasars such as 3C273 whose IR emission is $\sim 10^{48}$ ergs/sec. The upper limits of nuclei IR luminosities are equivalent to $\sim 10^{13}$ solar luminosities and correspond with complete conversion of about half a solar mass per year into energy.
5. The nuclei of many galaxies are strong radio sources

and in QSO's there exist small, strong radio source components only about a light year in diameter.

6. Energy and mass are ejected in bursts of various intensities and time scales. Mass ejection rates are typically $1M_{\odot}$/yr. Total energies of up to 10^{60}-10^{62} ergs (5×10^{6} to 5×10^{8} $M_{\odot}$ annihilated since birth of the galaxy).

On the theoretical side the following generalizations seem well established:

1. Interactions of stars and gas can lead to compact, high density condensations forming nuclei which evolve through phases of increasing density and decreasing angular momentum.
2. Black hole formation is possible in nuclei.
3. High efficiency conversion of mass into relativistic electrons is possible.
4. Nuclei may either be formed as part of a galaxy at its birth or later as a result of contraction of stars and gas toward the galactic center.
5. Evolutionary effects are important in QSO's, and N-galaxies, Seyfert galaxies, and quasars may be related.

The distillation of this information for students of this course would involve the concept of the existence of nuclei in most galaxies as sites of high stellar densities, with highly energetic events taking place possibly involving stellar collisions or black holes. Mass and radiation are emitted at sizeable rates and occasionally quite violent process occur leading to ejection of great jets of stars and matter and even sometimes to the explosive disruption of the whole galaxy. Some activity seems to be the normal accompaniment of all nuclei and ours is no exception. In fact, there is now evidence that ours ejected a modest pair of jets rather recently, some 13 million years ago. It is becoming increasingly evident that activity in nuclei may well be responsible for the energy output of quasars and that the latter are extreme cases of a progression of activity in galactic nuclei which ranges from rather well behaved ones like ours through increasingly active nuclei of compact galaxies, N galaxies, Seyfert galaxies, to Quasars. This progression in activity may even be an evolutionary sequence.

122. It has been pointed out earlier that the widespread existence of very old stars in all forms of galaxies seems to put an end to earlier ideas that irregulars, spirals, barred spirals, and ellipticals as arranged in Hubble's scheme represents an evolutionary sequence. Evidently the outer form of a galaxy is not determined mainly by its age but by other factors such as perhaps the angular momentum of the gas cloud from which it originally formed. On the other hand, it now appears that the size and density of the nucleus may be the age-related parameters.

The age of a galaxy can be estimated from the ages of its oldest globular clusters which are in turn judged from their turn-off points on the H-R diagram. This age in the Milky Way is from 8 to 18 billion years (the Sun's age is probably a little over 4.6 billion years). Another method of estimating the age of the Galaxy is by radioactive dating similar to C^{14} archeological dating but using long-lived radioactive elements such as U^{238} and Th^{232}. Ages in the range of 7 to 15 billion years are found by such methods (See Schramm, Sci. American, Jan, 1974).

Since the nucleus of a galaxy contains mostly old Pop. II stars, its color should not be contaminated by many blue stars and is therefore roughly indicative of its age. This is because the color of the integrated light from the nucleus is related to the M-S turnoff point of its more massive stars: the older the galaxy, the redder its color, other factors being equal. This last reservation is important and makes age determination by color rather uncertain, but color is all that can be observed in many cases and is therefore used, even if imprecise.

123. The use of cepheids, novae, and supernovae as distance indicators has been mentioned before and rests on knowledge of their intrinsic brightness from studies of such objects located nearby in our own Galaxy where distances can be determined by other methods. They are useful for distance measurements of external galaxies because they are rather easily recognizable and identifiable by the character of their light variation, and in the case of novae and supernovae they are intrinsically bright enought to be visible at great distances. This is especially true of supernovae.

124. This is a new concept for the student. If one studies nearby galaxies whose distances can be measured independently and tries to classify them according to form and size, as Hubble first did and as Morgan and his co-workers have done more recently with refinements, it turns out that there is a loose correlation between size, shape, and total light output which is good enough for estimating distances when the methods above fail because distances are too great to see cepheids or novae and there are no supernovae present. The method is basically similar to the use of the H-R diagram for stars. This is also a classification scheme relating intrinsic brightness to some other observable parameter (e.g., color or temperature). The classification schemes for galaxies also in many cases relate absolute luminosity to an observable parameter such as form; other schemes relate the size of a galaxy to the observable parameter. In either case the distance can be deduced.

125. This distance determinant is included here only for completeness. The next section explains it.

126. All standard texts treat Hubble's law more or less extensively. It may be worth noting that the value of the Hubble constant H in the expression v = Hr has been steadily reduced over the past few decades, as observations improve, from the value $\sim$500 km sec^{-1} Mpc^{-1} proposed by Hubble to the presently accepted value $\sim$ 55 km sec^{-1} Mpc^{-1} which is a recent revision from a value 75 km sec^{-1} Mpc^{-1} that has been stan-

dard for about 20 years. Sandage has said he would not be surprised if it were eventually found to be as low as 40 km/sec-Mpc. The Hubble law implies exponential radial expansion with a time constant, H^{-1}, and this "Hubble time" is an upper limit to the age of the Universe in the standard Big Bang cosmology. Thus, observational decreases in the accepted value of H imply increasing estimates of the age of the Universe in BB cosmology. Also, since v cannot exceed c, it follows that the maximum observable value of r must be $c/H = 5.5\text{x}10^3$ megaparsecs, or 17.5 billion light-years on the basis of this simple sort of BB cosmology.

127. The Hubble law can be verified for galaxies whose distances can be measured independently by some means such as those discussed above. This has been done for values of $z \equiv \frac{\Delta\lambda}{\lambda_o}$, the relative Doppler shift, out to about 0.1 with several important recent additions, near $z = 0.4$. These latter are especially valuable because they bring the verified Hubble law for galaxies up into the range of z-values where quasars are found. This does not prove that the quasar z-values are of Doppler origin, but it at least strengthens this argument.

128. Present the idea that the light by which we observe a distant object shows the object as it was long ago when the light we see left it. This is important in observational cosmology because if we look at sufficiently distant objects, we are also looking far back in time to an earlier and

presumably different looking epoch of the evolution of the Universe. A complication arises in that the galaxies may themselves be evolving so the "standard candle" they represent which we calibrate by nearby galaxies may be changing and the distances may not be what we judge them to be from apparent brightness.

129. Quasars have been observed with redshifts, $z \lesssim 3.5$. If these are Doppler shifts, the objects are receding from us at > 90% the speed of light, and they must be close to the horizon of the observable universe. Just how close and how far back in time we see them can only be specified on the basis of a particular cosmological model, but the look-back time is about 90% of the present age of the Universe in the most widely accepted BB model.

130. The old Hubble classification of galaxy shapes is found in the standard texts. Unfortunately, many of these impute evolutionary significance to Hubble's scheme. The more recent work of Morgan and various collaborators at Yerkes and several other modern classification schemes (those of Sandage and deVaucouleurs for galaxies in general, and those of Arp and of Vorontsov-Velyaminov for peculiar types, for example) are hardly mentioned in most texts. An exception is the text of Menzel, Whipple, and deVaucouleurs which, not surprisingly, gives a nice though quite abbreviated treatment of the Sandage and deVaucouleurs classification. The main point to get across about these schemes

is that they are all attempts to find meaningful correlations between observable features, hopefully as useful as the H-R diagram for stars. The matter is still open and is one of the active areas of astronomical galactic research at present.

131. This was discussed in Note 122 in connection with the Milky Way.

132. See standard astronomy texts. Some of the newer ones (e.g. Harwit (1973), Wyatt (1971) include the recently discovered Maffei galaxies in the Local Group. Galactic clustering has bearing on cosmology, the question being whether indeed matter is uniformly distributed throughout the Universe if considered on a sufficiently broad scale or whether on any scale, however large, the Universe is "grainy" and non-homogeneous.

133. Luminous wisps connecting galaxies (e.g., M51) are strong evidence that the galaxies are related and have probably collided. See the beautiful pictures on pp. 196-197 in Jastrow and Thompson (1974) showing a computer simulation of a collision between two galaxies. The collision rate for stars is negligibly small because they are so small and far apart. The Sun's nearest neighbor subtends 10^{-11} stearadian, for example. Galaxies are large enough and close enough in groups so the chance of a collision is not negligible. Such collisions do not involve stellar collisions but rather collisions of the gas clouds in each galaxy

with resultant heating of the clouds. There are also large tidal effects that pull gas and stars out of orbit to form the bridges often observed after collisions.

The most interesting but still controversial spatial alignments are those pointed out by Arp,[Sky and Telescope 38, 385 (1969)], [see also Burbidge, Annual Reviews, Vol. 8 (1970)] - apparent linear chains of galaxies far apart and stretching over large angles of the sky. These are believed by some to represent related galaxies that pose the difficult question how they can have maintained such alignments over such great distances and times; others feel they are simply co-incidental alignments and give statistical reasons to support this interpretation [see VanderLaan and Bash, Ap. J., 152, 621 (1968)]. At present, this matter is not settled but would have important consequences if Arp is correct. Taking into account the time scale from measured velocities ($\sim 10^7$-10^9 years.) which is short compared with the Hubble time or the ages of normal galaxies, these chains of galaxies may have been ejected form some "parent" galaxy, but the energetics of such ejection are mind boggling, on the order of 10^{58}-10^{60} ergs per event, and the nature of the event that could eject whole galaxies would certainly be something to speculate upon, but see notes on "White Holes" and "Worm Holes" further along (Note 150). As Burbidge (1970) concludes in commenting upon the Arp chains, "the history of astronomy over the last 20 years, particularly in the extragalactic field, does not suggest that a highly conservative approach is likely to be very fruitful". One of the most intriguing of Arp's examples is a pair of bridged galaxies (Markarian 205 and NGC 4319) connected by a star bridge and thus apparently having collided, whose red shifts are substantially different, too much so to be accounted for by the dynamics of the collision. (However, very recent image tube photographs of these objects by Lynds raises the possibility that the apparent connection seen in photographs may be an artifact of the photographic process). If these objects are in fact connected, they raise questions about interpretation of all red shifts as Doppler shifts. If these two galaxies are indeed bridged as photographs strongly suggest, they must be at nearly the same distance and ought to have the same red shifts according to Hubble's law. That they do not indicates either one has a large non-cosmological velocity (i.e. greatly in excess of its velocity due to expansion of the Universe) or that it has some added red shift not connected with the Doppler effect, perhaps a gravitational red shift. Other evidence for discordant red shifts has accumulated. For a review see Field, Arp, and Bahcall, "The Redshift Controversy," Addison-Wesley, Reading, Mass (1973).

134. The literature on cosmology at all levels has grown tremendously in the last decade. Most standard astronomy texts devote a chapter or more to the subject and a number of books have appeared recently which treat the subject in a

more or less non-mathematical way. One of the best of these, completely non-mathematical but quite up-to-date, is Kaufmann (1973). Also excellent, with just a few simple equations, is P. G. Bergmann's "The Riddle of Gravitation", Chas. Schribner's Sons, N. Y., (1968). An older but still worthwhile account is Bondi's "Cosmology" 2nd ed., Cambridge Univ. Press (1961), especially recommended for its treatment of the steady state theory. Finally, Sciama's, "Modern Cosmology" Cambridge, (1971), gives an excellent detailed account of the accumulation of evidence over the past decade in favor of the Big Bang theory. It is especially good in its description of the early, hot big bang with a discussion of the helium formation problem, and it gives a thorough discussion of the 3°K microwave background radiation and its significance. Sciama does not discuss black holes and related topics, however; for that and the simplest treatment of such topics as white holes and worm holes Kaufmann is recommended. Several papers in "Nuclei of Galaxies" (1971) also deal with black hole physics, and a paper in that volume by Morrison deals with spinars, massive objects with large angular momentum. Morrison also has a paper in Physics Today, March 1973, dealing with spinars as possible models for quasars. The spinar is envisioned there as a sort of super massive pulsar, a dense collection of 10^8-10^9 stars in a radius of ~ 1 light year, rotating with a strong, attached magnetic field and radiating by means of the pulsar's mechanism, whatever it may be, for efficiently converting rotational energy into radiation. The spinar is not a super-sized neutron star but a dense collection of normal stars in a small galactic-type nucleus. The important feature is that it makes use of the pulsar radiative mechanism.

135. What is meant by 3-dimensional analogs here is embodied in the familiar picture of an expanding universe in terms of spots on a balloon being inflated or raisins in a loaf of rising raisin bread. From any position, all the other "galaxies" (spots, raisins) in these analogs of expanding universes appear to recede.

136. The early stages in the Big Bang are surveyed by Novikov and Zel'dovich in "Annual Reviews Inc., Palo Alto, Calif. (1967), pp. 637-648, and in more detail in the same authors' book, "Relativistic Astrophysics," Vol. 2, U. of Chicago Press, Chicago 1975. See also Sciama's "Modern Cosmology," Chapters 12 and 13.

137. The important concepts for this course are that in the very early stages (times up to the order of 0.1 sec after the expansion began) matter, antimatter, and high energy radiation existed in equilibrium, but shortly thereafter the expansion had lowered the density and temperature so much that the gamma radiation-matter equilibrium became disconnected at $T \sim 10^9$°K and each went pretty much its own way. The relict radiation has now expanded and cooled so much that it has become the isotropic 3°K background microwave radiation ("Primeval Fireball")

detected a decade ago. There should also be an isotropic background of neutrino radiation as well, but it cannot be detected by any known method because of its low energy. Soon after the radiation-matter equilibrium had ceased, a similar equilibrium of matter leading to the present observed relatively large amounts of helium in very old stars, believed to represent the primeval composition of the gas in the universe (~28-30% He, the rest consisting of H with traces of D, and He^3, and Li^7 but no heavy elements) also ceased as the temperature dropped below a few times 10^9 degrees in the first few seconds after the expansion began. The amount of D produced has important implications for the question of whether the Universe is oscillating or infinitely expanding. [See Schramm and Wagoner, "Physics Today", Dec.,1974]. At some considerably later time, the temperature had fallen enough for first generation stars (old Pop. II) and galaxies to begin to condense, a process which we have seen would be expected to take times of the order of ten million years for the stars, i.e., the Kelvin contraction time for a solar mass star.

138. The Steady State cosmology of Hoyle, Bondi, and Gold is also an expanding cosmology in which galaxies recede from any point of observation. The difference is that this theory asserts that the large scale structure of the Universe never changes with time; as matter recedes, it is replaced by fresh matter being created everywhere at a very

slow rate ($\sim 10^{-47}$ gms/cm^3-sec or about 1 hydrogen atom per liter per century), too slow to be detectable but just enough to make up for loss of matter "over the horizon" which is set by the Hubble constant at a distance $c/H \simeq 13$ billion light years. This cosmology abandons strict conservation of mass-energy, regarding it as not an inviolable principle but as a physical hypothesis subject to test, and with so low a creation rate as to be well below limits of detectability the proponents of S.S. claim that creation does not violate experimentally established physical law. However, since conservation of mass-energy is also a consequence of the isotropy of space-time [see Wigner, "Symmetries and Reflections", Indiana Univ. Press, Bloomington, Ind. (196)] and since steady state cosmology is founded upon the perfect cosmological principle (see below) which also asserts space-time isotropy but requires creation of matter, there seems to be a fundamental inconsistency in the theory. Aside from such matters, the problems of satisfactorily explaining the 3°K background radiation and the high helium concentration in very old stars have proved to be serious stumbling blocks for such cosmologies.

139. The cosmological principle which asserts the large scale uniformity of the Universe from any space-like place requires a curved space-time in order to insure that the laws of physics are everywhere the same. But the so-called "perfect" cosmological principle which asserts that the Universe must

also appear the same at all times, the foundation of steady state cosmology, can be satisfied by flat space time with the space part of the metric expanding exponentially with time [see Bondi (1961), Ch. 12].

140. An important cosmological question is whether the Universe will continue to expand indefinitely or whether there is enough mass in it to bind it gravitationally so at some future time it will stop expanding and contract again, perhaps oscillating through successive expansions and contractions for all time. The critical mass density ρ_c that divides infinitely expanding from oscillating models may be arrived at approximately (and somewhat naively, but satisfactorily for present purposes) from Hubble's law which gives the recession velocity at a distance r (v = Hr) combined with the escape velocity from a spherical mass M of density ρ, namely $\frac{v^2}{2} = \frac{GM}{r} = \frac{4\pi\rho r^2 G}{3}$. These expressions yield $\rho_c = \frac{3H^2}{8\pi G} \sim 6\times10^{-30}$ gm/cm^3 with the presently accepted value of H ($\sim$55 km/sec-mpc).

141. To determine whether our Universe is oscillatory or indefinitely expanding, an estimate must be made of the actual density of matter and radiation, a very difficult job observationally. One of the best and most readable discussions of this task and its present status is to be found in Peebles, "Physical Cosmology", Princeton Univ. Press, Princeton, N. J. (1971). This is an excellent introduction for the instructor to a number of areas in modern cosmology, and it also discusses the critical density and its deriva-

tion in a more sophisticated way than the naive one given above. [See also the review of density by Goff, et. al. in Ap. J. 194, 543 (1974)]. Observational estimates give $\rho<\rho_c$ by about an order of magnitude but these estimates place a lower limit on ρ as a result of selection effects and observational difficulties. The deuterium argument (Note 137) also gives $\rho<\rho_c$ by about the same factor. Thus there is mounting evidence in support of an open Universe but the arguments and data in support of this conclusion are not yet conclusive.

142. There is another way to determine whether or not the Universe is gravitationally bound, by galaxy and radio source counts as a function of distance as measured by apparent brightness which is an easily observed quantity. There is a related but different observational test, the relation between redshift and apparent brightness. Both seek to look far back in time to determine how the Hubble constant may have changed with time. Different cosmological models of the Universe predict different forms of H(t). To date, the results are not very conclusive because they have not been carried to faint enough galaxies owing to observational difficulties of various kinds. But the evidence seems slightly to favor an ever expanding model though the uncertainty is large. The evidence does seem to rule out a steady state Universe, however, and in this respect it supports other evidence, chiefly the isotropic 3°K back-

ground radiation. Hodge ["Galaxies and Cosmology" McGraw-Hill, N.Y. 1966, Ch 14] gives some of the galaxy count and red shift vs. magnitude curve (after Sandage). More up-to date red shift data including radio sources is given by Sandage in "Nuclei of Galaxies", O'Connell, Editor, p. 615. Perhaps the main reason for showing these curves to the students is to impress them with the scatter in the data and the tentative nature of any conclusions drawn at this time. One of the chief problems with galaxy counts is due to the unknown effect of galaxy evolution on such data.

143. Since the known mass density is $<\rho_c$, an ever expanding universe would be expected. If this conclusion should eventually be shown to be incorrect and the universe to be oscillating and closed, there must be a considerable amount of mass or radiation in the Universe as yet undetected and unaccounted for. The shapes of rich clusters of galaxies and the spread in velocities of galaxies belonging to such clusters, on the basis of Virial theorem arguments, support the idea that there is much mass unaccounted for, and a number of ideas seeking to account for this missing mass in terms of gas, radiation, plasma, magnetic fields, dust and other intergalactic matter, cosmic rays, neutrinos and black holes have all been examined (see Peebles, pp. 86-117). However, at present [see Goff, et. al.] it seems unlikely that there is enough "missing" matter and radiation to raise ρ by the order of magnitude needed to make $\rho>\rho_c$

and close the Universe.

144. Both Peebles and Sciama deal at length with the 3°K isotropic background radiation and its cosmological consequences, and recent astronomy introductory texts say at least a little about it. Until very recently observations of the isotropic microwave background radiation had not included the crucial submillimeter wavelength range covering the peak in the 3°K blackbody radiation curve, and until these measurements were completed the black body nature of the radiation was not conclusively established. It is now regarded as definite that the spectrum is of blackbody radiation. Calculations strongly suggest that it originated in the Big Bang explosion as high energy gamma radiation, and as the Universe expanded it has redshifted to its present temperature of about 3°K. The observed very high degree of isotropy of the radiation (few tenths of a percent) implies two important conclusions: (a) the expansion of the Universe has been very isotropic and without clustering on a very large scale, and (b) the absence of any diurnal variations in the background radiation isotropy means that we cannot be moving fast with respect to the inertial frame of reference defined by the radiation. The upper limit on this velocity set by present measurements is $\sim$300 km/sec or roughly the speed at which the Sun revolves about the center of the Galaxy. Thus, "we" are not rotating with respect to the reference frame of the 3°K radiation either, because such

rotation would produce the same sort of observational anisotropies in apparent temperature and intensity of the background radiation as would linear motion, as a consequence of Doppler effects.

Probably the main things to get across regarding the 3°K background is that (a) it is a very strong argument in favor of a Big Bang type of cosmology and (b) its isotropy is strong evidence that the whole Universe is uniform on a grand scale, much better evidence for this than the observations of galaxies and radio sources.

145. Even the oldest stars appear to have relatively large concentrations (~25-30%) of He in their envelopes from spectroscopic evidence. Based on present knowledge of stellar evolution, there is no way this high He content could have come from the core where H burning is making He so it must represent the primeval He content of the gas from which these first generation stars were formed. It is a major task of cosmological theories to account for such high He content in the early Universe and this is a particularly hard problem for Steady State cosmology. Big Bang theories are more successful, attributing He formation to the high temperature, high density initial explosive phase. However, as detailed discussions show (see Peebles, for example) even in the BB theory, the matter is not so simple when one gets down to considering the finer points.

146. Jastrow and Thompson, Chapter 10, give a fairly good descrip-

tion of quasars and radio galaxies for purposes of this course. Perhaps more emphasis needs to be put upon the energies emitted by these objects,of the order of 10^{60} to 10^{62} ergs total during reasonable estimated lifetimes, corresponding to the total annihilation of as much as 10^{8} solar masses. The properties of N-galaxies, Seyfert galaxies, and quasars seem to form a continuous sequence from a morphological point of view, and all are prodigious emitters of energy if they are at distances given by their observed redshifts and Hubble's law.

If, as some hold, the large redshifts of the quasars are not all due to recession velocities but are in large part gravitational, then the objects may be closer, reducing the energy output needed to give their observed brightness. It has been suggested at the other extreme that the quasars may have been ejected at relativistic speeds from the nuclei of our Galaxy or from galaxies of the Local Group. If this occured long enough ago, all the objects would have passed us and would be receding from us, accounting for the absence of any observed blue shifts. They would not be so far away, however, as to cause a problem with energy production. On the other hand, they would raise an equally difficult problem of how large bodies can be ejected in toto from galactic nuclei. The existence of star bridges with substantial velocities between galaxies is cited as evidence that such processes do happen even if we don't know how.

A combination of cosmological and gravitational redshifts may be invoked to place the objects at intermediate distances, reducing the energy problem but requiring that the object possess an enormous gravitational field very nearly that of a massive black hole. Morrison and Cavaliere (in "Nuclei of Galaxies" and Morrison, in Physics Today, March 1973) have proposed such an object stabilized against collapse by spin, the "spinar", which has been mentioned in connection with pulsars which it resembles.

At present the problems of the quasar are still unsolved, and the students should be shown in a simplified way what these problems are and what is needed to make further progress. A reliable distance measurement that does not rely on Hubble's law would be of the greatest help.

147. Some QSO's have been found to vary in brightness on time scales of the order of a year. This implies that they are not more than about a light year in diameter (at least their radiation source is not larger than this). The same sort of physical argument was used to establish the size of a pulsar which was found to have rapid fluctuations in the pulses with time scales of about 10^{-4} sec. The general argument may be worth giving to the students: since information cannot be transmitted faster than the speed of light, and since parts of an energy radiating device must radiate

together, in phase, if they are not to cancel out each other's radiation at a distance, these coherently radiating parts cannot be farther apart than the light travel time in one period of the radiation frequency, or they can't tell well enough what each other is doing to be able to work together. This colloquial expression of the radiative coherence condition may be helped by an acoustical analogy using two (stereo) speakers driven by the same amplifier, one speaker having a delay line inserted into its feed line.

148. Violence in galactic nuclei has been treated earlier. Its cosmological significance lies in the possibility that such events may be energetic enough to account for the energy output of quasars if they are at distances corresponding with their redshifts.

149. Most energetic radio sources appear to be double or multiple sources, often with an optical galaxy of appropriate redshift lying midway between them. This suggests strongly that the radio emitters were originally ejected from the central galaxy . Again the energies involved are very large, implying tremendously energetic events in the nucleus.

150. Various suggestions for energetic processes in the nucleus include rapid supernovae explosive chains, frequent star collisions that produce explosive H and He burning or rapid evolution to supernova stages, formation of many spinning

black holes that accrete matter which radiates part of its mass away before it disappears, formation of spinars, or even explosive creation of whole galaxies by processes presently unknown.

A white hole is the inverse of a black hole, and if a black hole has angular momentum, it has been shown that matter which disappears down such a spinning black hole may not be trapped forever but may reemerge elsewhere in the universe. This point of reemergence is the white hole, and it would appear as a source of copious creation of matter. A black hole-white hole pair or a pair of topologically connected black holes are called "wormholes" or Einstein-Rosen bridges (see Kaufmann's "Relativity and Cosmology"). These things are sound enough mathematical entities, but their physical reality and properties are highly speculative. There is an appealing symmetry to the wormhole, however, that suggests what disappears down a blackhole somewhere in the Universe may be spewed forth to live again elsewhere, in the same Universe or in another. Such processes are ruled out for "ordinary" black holes with zero angular momentum, but spinning black holes ("Kerr holes") do seem to be able in principle to spew forth some of what they swallow. [See Boyer and Lindquist, J. Math. Phys. 8, 265 (1967)]. This mechanism could then account for copious "creation" of matter and energy in the nucleus of a galaxy containing a white hole. The fascinating questions like what determines the existence of a wormhole, is every black hole one end of a wormhole, what determines the space-time relation between ends of a wormhole, what happens to matter in the passage through such a thing, etc., etc., still remain to be answered.

151. The possibility of "life elsewhere in the Universe" is a question that intrigues most people, and students at this level will be interested in knowing how one goes about the task of estimating the chances of life elsewhere than on Earth. While the most recent astronomy texts have discussed the subject briefly and generally qualitatively, one must turn to one of the monographs on the field for details and numerical estimates. The best of these is by I. S. Shklovskii and C. Sagan, "Intelligent Life in the Universe", Delta, N. Y. (1966), and on a more popular, nontechnical, level Walter Sullivan's "We Are Not Alone", McGraw-Hill, N. Y. (1964) can be recommended.

The main ingredients in a rough quantitative estimate of the probability of extraterrestial life are listed in subheadings.

152. About 60% of the stars we can observe are double or higher multiples, and of these, roughly 1/6 or 10% of all stars are widely spaced binaries of surface temperature comparable to or less than that of the Sun. The significance of the latter point is that stars of spectral type "later" than F5

(i.e., surface temp. ~7000°K or less) have been found to be slow rotators like the Sun, and it is considered that the excess angular momentum of these stars may well be contained in planetary systems as in the case of the Solar System where the planets have 98% of the angular momentum. According to this view only the slowly rotating cooler stars are likely to have planetary systems. Thus, we have ~10% of all stars which are binaries widely enough spaced not to interact appreciably and cool enough to be slow rotators with the possibility of having planets. Of the 40% of all main sequence stars that are single, roughly half are cool enough to be slow rotators. Altogether, then, about 30% of all stars fit our crude criterion for possibly having planets.

153. Only a relatively narrow range of possible orbits place a planet at a distance from its sun that is suitable for life, i. e., such that the mean temperature does not differ much from that of Earth. Some simple, hardy forms of life may exist outside this temperature range, but not far outside of it. In the Solar System only ~ 10% of the planets (Earth out of nine planets) exist in the "zone of life". Is it a fair guess that other stars with planets will also have a counterpart of Earth at an appropriate distance? Both the planets and the moons of the larger planets such as Jupiter and Saturn roughly obey a relation known as Bode's

law (or Titius-Bode law) giving relative orbital radii (see standard astronomy texts and also Harwit pp. 29-31). Many doubt that there is any fundamental significance in Bode's law, but others think it may reflect something basic in the way planetary systems form, especially since it is repeated in the planetary satellite systems. Along these lines von Weizsacker has proposed a theory of the formation of the Solar System (see Physics Today, 1, 21 (June, 1946) and Struve and Zeebergs, "Astronomy of the 20th Century," Macmillan, N. Y. (1962 pp. 174) involving turbulent condensation of the solar nebula which leads in a natural way to Bode's law. Other theories (Berlage, Alfven, for example) also lead to a Bode-type relation in a more or less fundamental way. This is an important point, for if true, it virtually guarantees that every planetary system will have a planet in the "life-zone".

There is, of course, more to having life exist on a planet than insuring that its mean temperature falls within the right range. It must also have about the same mass as Earth and must rotate neither much faster or much slower. The right mass is needed to retain the atmosphere and to have a suitable gravitational acceleration at its surface. Some kinds of life forms are not very sensitive to "g" but presumably higher forms are. The chemistry of the planet is vitally important, as well. Life forms based upon carbon chemistry require water and oxygen, among other things, and the existance of water further restricts the range of physical conditions on the planet. The matter of rotation is related to extremes of day-night temperatures and indirectly to meteorology on such a planet.

154. It is not possible to see directly with the telescope a planet of even a nearby star if one exists. The planet is too faint, and scattered light from the star in even the best designed telescope would totally swamp the faint planet's image. One looks for planets by studying perturbations of the parent star's trajectory through space. A nearby star, Barnard's star (the second closest star system to us at a distance of ∿6 light years) has been found by this method to have perhaps two planets, one ∿ 1 1/4 the mass of Jupiter and the other ∿0.8 of Jupiter's mass. Statistically, it would be highly unlikely that such a nearby star would be found to have a planetary system unless such systems are commonplace.

155. In connection with the formation of amino acids, the experiments of Miller in the early 50's should be mentioned to the students. These showed that electrical discharges in a suitable primeval atmosphere containing H, C, N, O and water vapor were able to synthesize several simple amino acids in a relative short time at a high yield, ∿10%. There is no doubt, therefore, that given suitable conditions of temperature and atmospheric constituents on a

planet, these precursors to life will be formed.

156. It has been suggested that development of life, certainly in higher forms, requires a suitable sequence of geochemical evolution. Initially the atmosphere and surface of the planet where life forms must be non-oxidizing and liquid. The former prevents destruction by oxidation of initial amino acids thought to form in the atmosphere in electrical discharges, and liquid water is needed to support them, to provide mobility, and to provide the medium for their chemistry as they slowly form proteins and nucleotides, nucleic acids, DNA and eventually viruses, bacteria, and increasingly higher forms. At some point the atmosphere must become oxygen rich if any higher life forms are to develop; this shift from a reducing to an oxidizing atmosphere is aided by the development of lower life forms and some feel that the shift is almost entirely the result of early biological development. It is very hard to estimate the probability that all the conditions enumerated so far (and there are more) are met, mainly because our knowledge of the formation of the Solar System in particular and planetary systems in general is still so primitive. Cosmogony is one of the most difficult branches of astrophysics because so little room for error remains; our observations are so detailed and exact--we know so much about the Solar System-- that each bit of knowledge is a constraint on cosmogonic theory. With so many details to be satisfied by

any prospective theory, it becomes a formidable task indeed to make progress on this frontier. Yet without a fairly good theory, it is very speculative to estimate the probability that other planetary systems will contain suitably earth-like members whose geochemical histories are suitable for development of life in any higher forms. The matter is helped considerably by the enormous number of stars in the Universe, $\sim 10^{21}$ stars of solar mass, and as argued above statistically, we expect the order of 10^{20} of these may well have planetary systems. This is a mighty large number, and one can be exceedingly pessimistic about the various factors believed necessary for life development and still arrive at a large number of places in the Universe where higher forms of life can and presumably do exist. Shklovski and Sagan play this game of guessing the various probability factors and still come up with an estimated $\sim 10^{11}$ life supporting planets. Shapley has put it this way.

Suppose:

(a) only 1 star in 100 is a single star
(b) only 1 in 100 single stars has planets
(c) only 1 in 100 of these planet systems has an earth-like member
(d) only 1 in 100 earth-like planets has the right temperature range
(e) only 1 in 100 of these has the right chemistry

Then only 1 star in 10^{10} would be right for life to form. But this still gives 10^{11} such stars in the Universe, so if only 1 in 100 of such "suitable" planets actually has life well underway there would still be about a billion lifebearing planets in the Universe.

In the above estimate of the probable number of extraterrestrial life-sites in the Universe, the question of what kind of life might exist was not considered. "Life" in the probability calculation certainly does not mean humanoid life. The chances for such specialized development are very hard to estimate but are thought by most to be quite small. If we take Earth as an example and make the very naive assumption that all of the millions of species of life forms that exist and are estimated to have existed in the past are equally likely to form, then Man's chances would be something like 1 in 10^7 to 10^8, yielding a rather small number of other humanoid populations in the Universe, maybe only one, but certainly not a large number, much over 100. Again if these humanoid populations are randomly distributed in age or state of development, perhaps only half are on the average more highly developed than we are. But if, as some have argued, the discovery of nuclear energy represents a potentially major destructive crises in humanoid development, the number of populations that has successfully passed this crisis in which we now find ourselves is further reduced. Altogether, then, one must say that the question "Is Man Unique in the Universe" cannot yet be answered one way or the other on the basis of probability arguments, but it seems unlikely that he has more than a few, if any, counterparts elsewhere.

157. If this topic is discussed, emphasize the time and energy factors involved. It is often naively remarked that relativistic time dilatation will take care of the time problem for an interstellar traveller if he can accelerate to near the speed of light, arguing that only a one "g" acceleration for a year is needed to reach these speeds. But the energy balance is ignored. If a perfectly efficient conversion of fusion energy into propulsion were to be achieved only 0.7% of the fuel mass could be converted into spacecraft kinetic energy. A simple relativistic calculation shows that with this efficiency the spacecraft velocity could not exceed about one tenth the speed of light and at this speed time dilation is too small to appreciably decrease the traveller's aging process en route. At 0.1 c it would take 60 years to reach Barnard's star.

Interstellar communication can also be discussed on the basis of time and energy. Regarding time, the possibility of communication via tachyons might be mentioned (see Harwit for a brief discussion); at least the idea of a tachyon might be worth mentioning to the students. Otherwise, photon (electromagnetic) communication takes simply the time equivalent of stellar distance (light years) and would be exceedingly slow. The energy requirements and related technical requirements for transmission are nicely disclosed by Shklovskii and Sagan ["Intelligent Life in the Universe", Ch. 27] with the conclusion that narrow band radio communication with present technology should be possible over distances of a few tens of light years once contact has been made. The problems and uncertainties of making initial contact are also described, but as the preceeding note points out the prospects of finding a technically advanced civilization this close to us are very small, indeed. Technical requirements for search and communication over much larger distances, say over the Galaxy, seem quite beyond our capabilities now and in the forseeable future.

158. "Conceptual" means in this instance that the course is organized around unifying physical concepts or phenomena. For example, under the theme of gravitation a wide range of topics will be discussed from the motion of the moon about the earth to the motions of entire galaxies, all in the framework of gravitational interaction. Likewise the theme of electromagnetic radiation encompasses the radiative properties of stars and stellar systems while nuclear energy leads naturally to stellar evolution. Since the physical concepts are central to this approach the course emphasizes the physics in astrophysics. The teacher can mix the conceptual and traditional approaches to whatever degree he finds appropriate and can shift from one to the other in

certain areas. These notes are serially numbered to make it easier to refer to comments already given on topics in the traditional course, and this will be done freely to avoid repetition.

159. This list of themes and principle topics is meant to orient the student to the basic organization of the course. It should be made clear to him that there will be cases in which a given topic has to be treated under more than one of these themes. But basically each theme is a powerful unifying device that brings together in an understandable way a wide variety of astrophysical phenomena. Emphasize the value and economy of these unifying concepts, an idea that may be relatively unfamiliar to the non-science student. Try to convince him that a few well-learned principles will serve in lieu of much memorizing of facts and individual details.

160. Point out the importance of accurate determination of the Astronomical Unit as the primary distance yardstick of the solar system. It determines indirectly the mass and luminosity of the Sun from terrestrial measurements. See also Note(41).

161. Explain how radar works emphasizing the constancy of the speed of electromagnetic radiation independently of the motion of source, reflector, and receiver. Point out how far away the Sun is and that the reflected radiation received back on Earth is so small that only recently have

radars powerful enough and sensitive enough been developed to make this measurement possible. Cite the high accuracy of the method (determination of the A. U. to about 1 km).

162. This is basic to use of the inverse square law to determine distance from apparent brightness. This scheme only works if the intrinsic brightness (luminosity) is the same for all stars or, failing that, if some other observable property of a star gives a clue to its luminosity.

163. The mean spacing between stars in the "neighborhood" of the Sun (i. e. within about 300 light years) is roughly 3 light years. At this point it is convenient to introduce the concept of a light year as an astrophysical distance unit (See Note 33).

164. For nearby stars ($\lesssim$ 100 parces) trigonometric parallax gives a direct and unambiguous measurement of distance. Comparing this distance with distances obtained from the inverse square law a discrepancy becomes evident: not all stars have the same luminosity. In fact, stellar luminosities range over some 8 orders of magnitude. But despite so great a range of luminosity, it is safe to conclude that all these stars must be rather like the Sun in basic form, constitution, and energy source, i.e., all are spherical or very nearly spherical hot gaseous objects of roughly the same mass as the sun (within a factor 10 either way) consisting mainly of hydrogen and helium with small amounts of heavier elements, and fusing hydrogen into helium in the center to provide the supply of energy radiated away.

165. A sizeable fraction of visible stars are binaries revolving about a common center. The components of such pairs are at the same distance and so provide a good sampling of the ranges of luminosities, colors, masses, and compositions that stars may assume. These observed differences are, in the case of binaries, free from any distance effects that might confuse comparisons between single stars. Moreover, only for binaries can a simple, direct comparison of the masses of the components be made (via Keplers' 3rd law. See note 47). The spread in luminosities exhibited by components of binaries is the main thing to emphasize here; it shows clearly that not all stars have the same luminosity. Consequently, the inverse square law is not enough to determine distance. Some other observable property of a star is needed which gives us a clue to its intrinsic luminosity. Only then can the inverse square law give the distance in terms of intrinsic and apparent (observed) brightness.

166. The idea that color can be a measure of the temperature of a hot dense gas can be introduced here along with some basic concepts of thermal radiation (Note 34), particularly the idea that intrinsic luminosity increases rapidly with temperature and therefore that hot blue stars are much more luminous than cooler red ones. One has to be careful not to let the size of the star confuse the issue at this point since L depends upon stellar radius as well as upon temperature. (Note 46)

167. Describe the techniques but emphasize that what one is doing is reconstructing in a crude fashion the black body radiation curve from which the stellar surface temperature can be deduced, giving in turn the luminosity provided the radius is known.

168. Introduce the idea that the important physical parameters that determine the structure and observable radiative properties of most stars are M, L, T, R, and chemical composition (See Note 48, last part). If these can be determined, the whole structure of the star is uniquely determined. Thus temperature is a basic parameter, not color. But color is a measure of T, hence the usefulness of photometry with filters or other spectrally selective detectors. Photometry also measures the apparent brightness of a star seen in the telescope and so determines one of the factors needed to measure distance by the inverse square law.

169. This method assumes that the brightest galaxies in our neighborhood are typical of very bright galaxies elsewhere in the Universe. Over a considerable range of distances this hypothesis can be checked by using other means for measuring distance, and it has been confirmed that the most luminous galaxy in a cluster is almost always a giant elliptical galaxy with luminosity 10^{45} ergs/sec within a factor 2. They are therefore useful standard candles out to distances of 2 billion light years which is as far as they can be seen and identified.

170. These ideas can be introduced as in elementary physics first through the concepts of linear motion. Space-time diagrams can be introduced in the usual form with t as abscissa and also in the Minkowski form with t as the ordinate. Due allowance should be made for the non-science students' lack of familiarity with such graphical presentations.

171. The Galilean concept of relativity can be introduced nicely through Einstein's famous moving train example. The main point to get across is that physics experiments done on a moving platform do not reveal the motion of the platform if this motion is unaccelerated. In a similar fashion the connection between gravitation and uniform acceleration can be illustrated with Einstein's free-falling elevator example in which gravity can be locally transformed away in a suitable uniformly accelerated reference frame, the elevator.

172. Conservation laws in general can be introduced here and some effort made to convince the student of their usefulness in physics. Conservation of energy can be presented both as an experimental fact and as a consequence of the isotropy of space-time, introducing the sophisticated connection between symmetry principles and conservation laws in physics.

173. This can be treated in the circular orbit case in terms of gravity balancing centrifugal force. The importance of the natural satellite motions is that they provide a simple

observational verification of Kepler's laws in a much more direct way than the motions of the planets about the Sun.

174. Give the general properties of elliptical orbits. Introduce the concept of binding energy, and explain how families of similar orbits but differing energy are related. Describe hyperbolic orbits as those of systems of positive total energy. (Comet orbits as examples). Cite the example of collisions between bodies with inverse square law attraction. Explain escape velocity and cite the $\sqrt{2}$ ratio between escape velocity and circular orbit velocity. Some numbers that refer to Earth satellites should be mentioned such as the ∿18,000 mph velocity of an artificial satellite in a circular orbit vs. its velocity (∿25,000 mph) needed to head off for the Moon. The velocity to escape from the solar system (∿95,000 mph) from a circular orbit at the mean position of Earth can also be given.

175. See Note 18. In the conceptual approach it is appropriate to emphasize the great generalization accomplished by Newton. From just two simple laws Kepler's laws are readily derived, and all the details of planetary motion (except the very subtle ones that are of relativistic origin) can be obtained. Cometary (hyperbolic and parabolic) orbits are likewise contained in Newton's laws and all the complex motions of artificial satellites travelling to the Moon or the other planets. Explain that this kind of synthesis of many complex details into a few simple laws is what physics always

seeks to accomplish, a point that is generally not appreciated by the non-science student.

176. The intent here should be to give a broad picture of sizes and shapes of planetary orbits in the Solar system. See also Note 19.

177. The binary star systems provide observational information about stellar masses. The standard astronomy texts give details. The technique is a direct application of Kepler's law and should be presented in this context.

178. The importance of the mass-luminosity relation in astrophysics can be illustrated from two points of view: (a) mass and chemical composition are the primary variables that determine the structure of a star (Note 48) and both members of a binary would be expected to have been formed at about the same time out of the same material and ought therefore to have the same chemical composition, even though their masses may be different. The relation between M and L, unaffected by variations in composition, should therefore be observable in binaries and leads to the observed mass-luminosity relation (see any astronomy text); (b) since mass and composition determine the structure and therefore the luminosity, radius, surface temperature, etc. of a star, it follows that theoretical stellar models must give rise to a theoretical M-L relation which in turn must agree with the observed one if the stellar structure has been

correctly calculated. Emphasize the role of this kind of check between theory and observation or experiment in physics.

179. The chief points to get across here are that dynamically star clusters, galaxies, and clusters of galaxies behave similarly. All are gravitationally bound systems with many very small elements of matter in mostly empty space. There are two principle types of motion: (a) random, with the mass elements (stars in clusters, stars and clusters in galaxies, and galaxies in clusters of galaxies) moving in swarm-like motions as molecules in a gas but with about no collisions because the mass elements in clusters, etc., occupy fractionally very much less space than do molecules in a gas, (b) rotational motion due to conservation of angular momentum as the object (cluster, galaxy, etc.) condenses out of its parent object (gas cloud). It can be shown that such condensing rotating objects evolve into disk-like objects with most of the mass concentrated in the equatorial plane. Most clusters and galaxies are a combination of these two modes of motion, the predominant form depending upon the relative amount of angular momentum. Baade's 2 population classification of stars and clusters in the Galaxy is a simple way of separating the objects in the Milky Way into those constituting the halo or swarm of largely spherically distributed, randomly moving stars and clusters, on the one hand, and the disk constituents with considerable angular momentum about the galactic

center on the other. The observational differences between these Pop. I and Pop. II groups is treated in standard texts. Star clusters and galaxies behave this way; clusters of galaxies appear to behave similarly but the consequences are not so evident to the eye because clusters of galaxies all seem to have relatively little rotational flattening.

180. The geological information putting the age of the Earth at about 4.7 billion years is treated in modern texts. Moon rocks give independent support for an age over 4 billion years. Theories of evolution of stars like the sun are on firm ground and give the age of the sun at $\sim$5 billion years.

181. The oldest clusters in the Milky Way are the ellipticals and their ages can be inferred from the temperatures of their hottest stars (i.e. from their turn-off-point on the H-R diagram) together with information from stellar evolution theory that relates age to turn-off point. The oldest of these clusters is about 10 billion years so the Galaxy must be at least this old.

APPENDIX A: RECOMMENDED SLIDES FROM HALE CATALOG

Slide numbers are from "Catalog of Photographs and Slides from the Hale Observatories" available from the California Institute of Technology Bookstore, 1201 East California Blvd., Pasadena, California 91109.

(1) Color slides

Cat. No.	Object	Remarks
S-19	North American Nebula in Cygnus	Shape caused by dust cloud against starry background
S-20	A portion of the Veil Nebula in Cygnus	Gaseous nebula, believed to be supernova remnant
S-21	Ring Nebula in Lyra	Planetary nebula, central star visible
S-22	Crab Nebula in Taurus	Supernova remnants. Contains pulsar
S-23	Great Nebula in Orion, central region	Region of active star formation
S-24	Great Spiral Galaxy in Andromeda	Similar to Milky Way Galaxy
S-25	Lagoon nebula in Sagittarius	Gaseous nebula excited by radiation from hot, blue star
S-26	Dumbbell Nebula in Vulpecula	Planetary nebula, central star obscured
S-27	Spiral galaxy in Sculptor	Type Sc spiral
S-28	Large spiral galaxy in Triangulum	Type Sc spiral, very open arm structure
S-29	Trifid Nebula in Sagittarius	Gaseous nebula, very dusty gassy region. Emission nebula on right is illuminat by hot, imbedded star.

Cat. No.	Object	Remarks
S-30	Pleides in Taurus	Famous "Seven Sisters" of winter sky. Emission nebulae gas illuminated and excited by hot, blue stars
S-31	Comet Humason	
S-32	Horsehead Nebula in Orion	Dark cloud of dust against bright star and gaseous nebular background.
S-33	Rosette Nebula in Monocerous	The red color is H-alpha line emission, 6563A
S-34	Irregular galaxy in Ursa Major (Big Dipper)	A radio source
S-35	Nebula in Serpens	Unusual gaseous Nebula
S-36	Omega Nebula in Sagittarius	Strong H_α emission nebula
S-37	Planetary Nebula in Aquarius	Large planetary. Central star visible. Similar to "Ring" nebula in Lyra
S-38	Spiral galaxy in Pegasus	Type Sb spiral
S-39	Planetary Nebula in Aquila	
S-40	Mars	
S-41	Jupiter	
S-42	Saturn	

(2) Black and White Slides

Cat. No.	Objects	Remarks
2	Galaxy in Andromeda	This is an elliptical galaxy Satellite of "Great" Galaxy, M31.
4	Galaxy in Pisces	Spiral, Type Sc

Cat. No.	Object	Remarks
5	Galaxy in Eridanus	Barred spiral Type SBb
6	Nova Persei	Nova of 1901, photographed in 1949
10	Cone Nebula in Monocerous	Gaseous nebula with dark dust cloud
19	Group of 4 galaxies in Leo	Most prominent is barred spiral, Type SBa
30	Globular Cluster in Canes Venatici	Perhaps 100,000 stars in spherical, gravitationally bound group
50	Populations I and II	Spiral arm of NGC 224 in blue light and NGC205 in yellow light
53	Cygnus "A" radio source	Believed to be a binary star, one member of which is a black hole
63	Galaxy in Centaurus	Strong radio source, Centaurus "A". Peculiar galaxy
65	Group of galaxies in Serpeus	Five galaxies with unusual connecting clouds
68	Hercules Cluster of galaxies	Many different types of galaxies gravitationally bound in a huge cluster
69	3C295 in Bootes	Picture and spectrum of very distant radio object, a QSO or quasar with large-red shift
100	Great Galaxy in Andromeda	Central region
101	Great Galaxy in Andromeda	South region resolved into individual stars
127	Galaxy in Andromeda	Type Sb seen edge-on. Thin dust disk is evident

Cat. No.	Object	Remarks
138	Six spiral galaxies	Shows types SO, Sa, Sab, Sb, Sc
139	Six barred galaxies	Shows types SBO, SBab, SBb, SBc
201	Milky Way, Sagittarius region	Wide angle view toward the center of the Milky Way
230	Solar disk and enlarged sunspot	Very large sunspot (1947)
233	Solar disk	4 views: (a) White light, (b) Red light (H_α), (c) Violet light (Ca K), (d) enlarged view of sunspot in H
234	Spectroheliogram of whole solar disk (Ca K)	Shows prominences
238	Solar corona	Photographed during total eclipse
240	Sun, at sunspot maximum (1957)	
245	Solar granulations	Highly magnified solar surface showing turbulence
246	Spectroheliogram of part of Sun (H_α)	Spectroheliograph is instrument to photograph Sun by light of very narrow wavelength range
247	Solar prominence	Over 1/4 million miles high
251	Moon, crescent phase	8 days after new moon; near first quarter
253	Moon, full phase	14 days after new moon
255	Moon, crescent phase	20 days after new moon; near last quarter
260	Crater copernicus on Moon	
261	Moon, central region	Last quarter, shows craters Ptolemy and Eratosthemes

General notes about the slide shows

The purpose is to capture the students' attention and interest at the outset by showing him something of the variety of objects he will be learning about later. The instructor may adopt either of two approaches to the slide show. He may pose questions to pique the students' curiosities, questions that will eventually be answered. For example,

Moon--why is our nearest neighbor so different from Earth?

Mars--why like the moon in some ways but like Earth in others?

Jupiter--why is it almost a star yet has a very cold surface?

Sun--what is the source of its intense heat? As the only star we can see in detail, is it like other stars? How was it formed? How will it change in time? Why? Is the solar system unique?

Star field--all these points of light are stars. How can we find out about them: their distances, motions, temperatures, masses, internal makeup?

Planetary nebula--Why did the star throw off a shell of gas? Will the Sun do this?

Crab nebula--some stars change violently. What causes such stellar catastrophes? Are they common events?

Hercules Cluster--a great collection of 100,000 stars bound together by gravity, almost a mini-galaxy. The oldest known cluster in our Galaxy (10-12 billion years old). How do we know its age?

Andromeda--a galaxy similar to ours. How do we know this?
How do we find out what our galaxy looks like
when we're inside it?

This list is just given as an illustration of this approach.

The other approach is to describe each object very qualitatively and simply. For example, the Orion nebula might be described by saying that we believe stars are formed by vast condensing clouds of dust and gas that are squeezed down by gravity until they become hot enough to ignite nuclear energy producing processes. Thus we look to dusty regions for new stars to form and the Orion nebula is just such a place. Its very appearance in the slide is dramatic and suggestive of the presence of new, hot, blue, bright stars that light up the surrounding gas and dust and create cosmic pictures like the Horsehead Nebula for us to see.

Either approach must intrigue the student and stir his interest. This is no time for details or complications; just a broad brush is called for. Try to show something of the great variety of things that nature has provided to study but point out that we can make sense out of this large variety by using a few simple physical ideas. Try to avoid making the slide shows too long. Not all the slides listed should be shown in the two scheduled shows. Some are well suited for presentation with the topics they deal with, for example, the slides 233, 234, 238, 240 might be reserved for the lecture on the Sun or if shown in the first show, they might be presented again at the lecture covering the Sun. Likewise some of the spectacular color pictures of nebulae can be shown in both shows if desired. The second show concentrates upon nebular objects but these are also worth showing with less detailed comments at the first show because of their beauty and dramatic impact.

APPENDIX B: SOURCES OF ASTRONOMY FILMS, PHOTOGRAPHS, AND SLIDES

A. F. Films, Inc.
Room 1001
1600 Broadway
New York 19, New York

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois
  Attention of Technical Information
  Division Films Library, D2-Wing G

Association Films, Inc.
347 Madison Avenue
New York 17, New York

Astronomical Society of Switzerland
Slides Department
8200 Schaffhausen
Switzerland

35mm color slides, available only in sets of 6 or 8.

Astronomy Charted
Route 2, Coach Road
Argyle, New York 12809

35mm black and white slides; 8 1/2 x 11 and 27 x 35 charts; catalogue available free to educational institutions, 50¢ to individuals.

Audio-Visual Center
University of Indiana
Bloomington, Indiana

Audio-Visual Education Center
University of Michigan
Ann Arbor, Michigan

Byron Motion Pictures, Inc.
1226 Wisconsin Avenue, N.W.
Washington 7, D. C.

Public Relations
California Institute of Technology
1201 East California Street
Pasadena 4, California

Carousel Films, Inc.
1501 Broadway CBS Film Series
New York 36, New York

Chicago Public Library
Visual Materials Center
78 East Washington Street
Chicago, Illinois 60602

Contemporary Films, Inc.
267 West 25th Street
New York, New York

Rental copies of UNIVERSE (a 28-minute 16mm black and white sound film from the National Film Board of Canada, 680 Fifth Avenue, New York); the film can serve as an introduction to astronomy for elementary and high schools, or for general adult audiences.

Coronet Instructional Films
Coronet Building
Chicago, Illinois 60601

Edited Pictures System, Inc.
165 West 76th Street
New York 19, New York

Educational Testing Service
20 Nassau Street
Princeton, New Jersey

General Electric Company
Missile and Space Vehicle Dept.
3198 Chestnut Street
Philadelphia 4, Pennsylvania

High Altitude Observatory
University of Colorado
Boulder, Colorado

Hubbard Scientific Company
P. O. Box 105
Northbrook, Illinois 60062

Color postcards; 35mm black and white and color slides and 8 x 10 prints from Mount Wilson and Palomar Observatories; also charts, overhead transparencies, and models (including celestial globes).

Illinois Bell Telephone Company
208 West Washington Street
Chicago, Illinois 60606

International Film Bureau, Inc.
332 South Michigan Avenue
Chicago, Illinois 60604

International Screen Organization
1445-18th Avenue, North
St. Petersburg 2, Florida

5 astronomy films (16mm black and white sound films) on the sun, the moon, the solar system, the Milky Way, and external galaxies; also 35mm black and white.

Knowledge Builders
625 Madison Avenue
New York 22, New York

Louis De Rochemont Associates Film Library
267 West 25th Street
New York 1, New York

McGraw-Hill Text Films
330 West 42nd Street
New York 36, New York

Modern Learning Aide
1212 Avenue of the Americas <ins>or</ins> 160 East Grand Avenue
New York, New York 10036 Chicago, Illinois 60611

2-28 1/2-minute color films prepared by the American Astronomical Society for classroom use; both <ins>A Radio View of the Universe</ins> and <ins>Exploring the Milky Way</ins> are available for loan or purchase.

National Film Board of Canada
680 5th Avenue
New York 20, New York

National Audiovisual Center
National Archives and Records Service
Washington, D. C. 20408

APPOLO 11 (a 28-minute 16mm color sound film) for sale to school and community libraries.

Teaching Film Custodians, Inc.
25 West 43rd Street
New York 18, New York

United World Films, Inc.
1445 Park Avenue
New York 29, New York

U. S. Government Printing Office
Book Store
219 South Dearborn, Room 1463
Chicago, Illinois 60604

or

Superintendent of Documents
U. S. Government Printing Office
Washington, D. C. 2040

Apollo 11 x 14 color photographs; 16 x 20 color prints of paintings on space subjects; NASA books and pamphlets.

World Data Center A
High Altitude Observatory
University of Colorado
Boulder, Colorado

copies of *A Continuous Solar Movie*, 6-20 July 1959, for purchase or loan.

World in Color Productions
Elmira, New York

Young America Films, Inc.
18 East 41st Street
New York 17, New York

APPENDIX C: RECENT POPULAR ARTICLES FOR STUDENT REFERENCE

The X-Ray Sky. Liller et.al. Sky and Telescope 48,289 (1974); 48, 347 (1974); and 49, 10 (1975).

Some Current Problems Concerning Galaxies. J. B. Irwin. Sky and Telescope 46, 287 (1973).

Photometry of UV Ceti Stars. T. J. Moffett. S. and T. 48, 94 (1974).

A Visit to Tycho Brahe's Observatory. E. Simonsen. S. and T. 47, 1974).

Supernova Remnants. Paul Gorenstein and Wallace Tucker. Scientific American 225, 74 (1971).

The Gum Nebula. Stephen P. Maran. Scientific American 225, 20 (1971).

Intercontinental Radio Astronomy. K. I. Kellermann. Scientific American 226, 72 (1972).

How Did Kepler Discover His First Two Laws? Curtis Wilson. Scientific American 226, 92 (1972).

Prematurity and Uniqueness in Scientific Discovery. Gunther S. Stent. Scientific American 227, 84 (1972).

Interstellar Molecules. Barry E. Turner. Scientific American 228, 50 (1973).

The Chemistry of the Solar System. John S. Lewis. Scientific American 230, 50 (1974).

Deuterium in the Universe. Jay M. Pasachoff and William A. Fowler. Scientific American 230, 108 (1974).

The Cosmic Background Radiation. Adrian Webster. Scientific American 231, 26 (1974).

The Search for Black Holes. Kip S. Thorne. Scientific American 231, 32 (1974).

X-Ray Emitting Double Stars. Herbert Gursky and Edward P. J. van den Heuvel. Scientific American 232, 24 (1975).

APPENDIX D

PARTICIPANTS OF FACULTY WORKSHOP IN ASTROPHYSICS--UNIVERSITY OF ILLINOIS AT CHICAGO

Summer 1974

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